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TRANSIENT AND TEMPORARY SWITCHING OVERVOLTAGES IN 230 kV GRAVATAÍ CAPACITOR BANKS – STRESSES IN THE BANKS, SUBSTATION EQUIPMENTS AND ASSOCIATED SYSTEM

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Abstract – **Transient overvoltages and overcurrent studies were performed to evaluate the stresses in the capacitive units of the two 100 MVAr/230 kV shunt capacitor banks of the Gravataí substation. Current limiting inductors were dimensioned to satisfy the current transformers secondary side voltage withstand limits. Effect of transient overvoltages in far away substations was verified. The paper describes the new developed evaluation criteria, for transient and temporary overvoltages evaluation in capacitor units, to comply with the requirements of the standards and the operating conditions expected to occur in real operation.**

Keywords: Overvoltages, Modeling, Controlled Closing, Evaluation Criteria.

I. INTRODUCTION

Gravataí is a large 500/230 kV substation, located in a strategic electric point of Rio Grande do Sul State, Southern Region of Brazil, where .the 500 kV area belongs to the Empresa de Transmissão do Sul do Brasil S.A. – ELETROSUL and the 230 kV one, to the Companhia Estadual de Energia Elétrica – CEEE. Due to this peculiarity, any equipment inside the substation is likely to receive electric stresses from 230 and 500 kV as well.

The already existing 100 MVAr/230 kV shunt capacitors bank of CEEE, not having a current limiting inductor, was not sufficient to keep the reactive power and voltage requirements at a minimum acceptable level, during the summertime load. So, two additional 100 MVAr/230 kV shunt capacitors banks with current limiting inductor, belonging to ELETROSUL, had to be installed up to December 1999, in the 230 kV area of CEEE.

In addition, even before the consideration of two additional banks, dielectric failures in 230 kV CEEE transformer bushings occurred and it had been previously supposed to be related to the switching of the first bank, resulting in restriction of its operation.

As a consequence, the technical specifications required a significant number of overvoltage/overcurrent studies, involving energization, restrike conditions of each capacitor bank as well as simulations of switching operations in 230 kV and 500 kV systems (load rejection and fault application/clearing), leading to temporary overvoltages produced by transformer saturation in conjunction with the change in the frequency response of the system seen from Gravataí 230 kV busbar, for different number of capacitor banks connected.

Another aspect considered, even not required in the technical specifications, was the evaluation of the undesired overvoltages in the adjacent and remote substations, any time capacitor banks were switched in.

The specified number of daily capacitor bank energizations resulted in significant discussions on how to consider the limits recommended by the IEEE/ANSI CP-1-1988, concerning the volts-time short duration maximum overvoltages, when analyzing the simulation results. This gave rise to new evaluation criteria, which will be described along this paper.

II. A BRIEF SYSTEM AND STUDY DESCRIPTION

Gravataí is a very large substation fed by two 500 kV long lines from Eletrosul's bulk power transmission system, by means of four step-down 600 MVA 500/230kV transformer. In turn, the 230 kV busbars feeds ten 230 kV transmission lines and two local 230/69 kV step-down transformers, in the 1999 configuration. In near future (2008 configuration), the number of 230 kV transmission lines will increase to around fifteen.

The study was performed using the ATP program and was divided into the following parts:

a) Capacitors bank energization;

b) Capacitor current discharge over short-circuit conditions inside the substation;

c) Transient and temporary switching overvoltages in the system;

d) Transient Recovery Voltages (TRV studies);

e) Circuit-breaker restrike conditions on the capacitors;

f) Lightning Overvoltages.

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In a general way, studies (a), (c), (e) and (f) had the main purpose of evaluating the transient and temporary overvoltage conditions on the capacitor units. These results were useful in the evaluation of the voltage stresses in the overall substation equipments as well. Item (b) and (e) were directed towards the current stress effects in capacitive units as well as in the current transformer's secondary side and in the line traps. Item (d) was involved with opening conditions of the shunt capacitors banks.

The system model represented all three phases, the lines were represented by positive/zero sequence distributed parameters and magnetic flux versus current characteristic of every power transformer inside the substation was modeled. Loads were represented as R, L series equivalent circuits, based on the load-flow conditions calculated previously by a traditional load-flow program; these same load-flow results were also used to establish the initial conditions for the transient studies. Substation busbars were represented by equivalent R, L circuits, taking into account busbar lengths, in the region of interest.

The worst closing times of capacitors banks circuit-breakers was chosen from statistical energization simulations taking as control parameters the maximum overvoltages and overcurrents in the switched capacitor bank; circuit-breakers three-phase maximum closing time span was 5.5 ms (120^0 electrical degrees).

Similarly, systematic switch model was used to calculate the worst condition of short-circuit application time in the voltage wave.

In cases where evaluation criteria had been exceeded, a sensitive analysis was performed considering the frequency dependence of the resistance of some components, in the predominant frequency of the phenomenon.

As an useful tool for the temporary overvoltage analysis, in order to identify the parallel resonance points, frequency responses of the system until around 1 to 2 kHz, seen from the 230 kV substation busbar were performed.

The calculations considered both system configurations (1999 and 2008), combined with one, two or three capacitor banks in service.

III. OVERVOLTAGE AND OVERCURRENT EVALUATION CRITERIA

In order to evaluate voltage and current stresses in the capacitor bank components as well as in all other equipments of the substations, specific evaluation criteria were developed.

1 – <u>Acceptable overcurrent and overvoltage in the capacitor units</u>

The transient stresses in capacitor units were evaluated considering the recommended values of ANSI CP-1-1988, as proposed by the manufacturer.

The ANSI values, for transient overvoltages and overcurrents are shown in Tables 1 and 2, in which it was assumed a duration of around one or two cycles of fundamental frequency waveform.

Number of transients/year	Maximum Permissible Value (pu of rated voltage)
40	4.0
400	3.4
4,000	2.9

Table 1 – Maximum Transient Overvoltages

Number of Transients/year	Maximum Permissible Value (x I_{RATED})
2	1,000
1,000	100

Table 2 – Maximum Transient Overcurrents

For temporary overvoltages in capacitor units, the values of Table 3 were used.

Duration	Maximum Permissible Voltage (pu of rated voltage)
15 cycles	2.00
1 sec.	1.70
15 sec.	1.40
1 min.	1.30
30 min.	1.25

Table 3 – Maximum Short-Duration Voltages

These values are based in the fundamental frequency waveform (60 Hz), limited to a combined number of occurrences lower than 300 times, during the capacitor lifetime.

Special attention was paid to the question of the expected number of overvoltage application during the lifetime, cumulatively stressing the capacitor unit insulation, because each capacitor bank in the substation will be energized one or two times a day.

The total average expected number (N_T) of daily transient events in the capacitor units was computed as being $N_T = N_E + N_R$ (1), where N_E is the average number of daily energizations of the capacitor banks, including those affecting the parallel banks already in service. N_E can be calculated as $N_E = \frac{\sum_{i=1}^{n_B} i}{n_B} \cdot n_D$ (2), with n_B being the number of switchable capacitor banks and n_D, the number of daily switching operations required.

For N_R, the average number of circuit breaker restrikes in daily operations, when opening the capacitive currents, was computed as $N_R = p_R \cdot N_E$ (3), with p_R being the restrike probability of the circuit breakers, for capacitive current opening conditions.

Generally speaking, the N_E is predominant on N_T, so that $N_T \gg N_E$. So, overvoltage amplitudes associated with circuit-breaker restrikes as well as with any other low probability phenomena, could be treated separately, mainly if its amplitude is significantly large, compared with those of energization operations.

To take into account the effect of voltage/current distribution along the capacitor units, when some internal element had failed (internal fuses, in our case), the amplitude limiting values of the Tables 1 to 3 were corrected, to represent this effect on the most stressed capacitor unit, just before the current unbalance protection could trip the bank out.

Tables 4 and 5 are the previous Tables 1 and 2, for the same one or two cycles transient overvoltage/overcurrent durations.

Number of transients/year	Maximum Permissible Value (pu of rated voltage)
40	3.63
400	3.08
4,000	2.63

Table 4– Corrected Maximum Transient Overvoltages

For n_D = 1 daily operation, n_B = 3 and the assumed p_R = 0.5%, we arrived to N_T = 734 occurrences/years; for n_D = 2 daily operations, n_B= 3 and the same restrike probability, we came to N_T = 1.460 occurrences/years.

Number of Transients/year	Maximum Permissible Value (x I_{RATED})
2	903.0
1,000	90,3

Table 5 – Corrected Maximum Transient Overcurrents

The corresponding transient overvoltage/overcurrent limiting values, used in the simulations, for one to two cycles duration are shown in Table 6:

Daily operations	Transient Overvoltage (pu of rated voltage)	Transient Overcurrent (kA_{crest}))
1	2.63	32.1
2	2.63	To be confirmed with manufacturer

Table 6 – Transient Overvoltage/Overcurrent Limits

Finally, the criterion for temporary overvoltage evaluation, based on Table 3 values is described below.

Amplitude values were corrected with the same factor used for transient overvoltage table. Here, an additional feature appeared: how to consider the number of combined occurrences lower than 300, during the lifetime.

Indeed, the main consideration was that all the points of Table 3 belong to an inverse curve, below which no significant loss of lifetime should occur, as long as the number of combined occurrences in the lifetime is limited to 300.

The limitation was concerned with the cumulative effect of insulation degradation, mainly due to partial discharge process (entering in PDIV / leaving PDEV, each half-cycle), that could lead to a strong reduction of lifetime of the capacitor units. Table 3 was transformed in Table 7, as shown below.

Semi-cycles/Switching Operation		Maximum Overvoltage
One Daily Operation	Two Daily Operation	(pu of rated voltage)
-	-	1.81
2	1	1.54
29	15	1.26
119	59	1.17
3,533	1,766	1.13

Table 7 – Capacitor Temporary Overvoltage Limits.

The number of semi-cycles, in the Table 7, was calculated transforming the durations in the Table 3, in semi-cycles of fundamental frequency, taking into account the 300 occurrences in the lifetime and N_T, already calculated.

2 - <u>Current transformers secondary side's overvoltage limits</u>

Using the transient CT secondary side voltage relationship of ANSI C.37.0731 – 1973 (V_S), we can derive the I.F product on its primary side, assuming V_S = 5,0 $kV_{peak.}$

$$I.F = \frac{V_S \cdot CR}{2p \cdot L} \quad (4)$$

, with CR being the CT current ratio and L, the inductance of the CT burden.

3 – <u>Transient overvoltage limits in overall equipments</u>

For transient overvoltage limits, it was considered that maximum transient overvoltage should not exceed V_T(máx) = BIL x 0.83 x 0,90 (life degradation)x 0.833 (surge arrester protective level).

4 - Temporary overvoltages in transformers

The criterion normally used by the Brazilian National Grid Operator (ONS), in case of load rejection transient overvoltages, is that 1.4 pu rated voltage should be maintained only by 20 cycles of fundamental frequency.

5 – Transient Recovery Voltages

As per IEC standards, covering short-circuit and capacitive current interruption.

IV – SOME STUDY RESULTS

4.1 Capacitors bank energizations

Table 8 shows the maximum overvoltages in the banks and their corresponding overcurrents, obtained for the worst cases of the 1999 and 2008 configurations; cases of maximized overcurrents were also used to obtain the worst I_{crest} and I.f product, for energizations conditions.

Banks 2 (B2) and 3 (B3) are the new capacitor banks; Bank 1 (B1) is the existing one.

The instant of closing on each phase was selected by statistical switching cases, trying to maximize the overvoltages and overcurrents.

Case	Overvoltages (pu) (*)		Overcurrents (kA_{crest})	
	Bank 2	Bank3	Bank2	Bank3
B3 switches, B1 and B2 on, 1999	1.63	1.62	5.00	6.10
B3 switches, B1 and B2 on, 1999, sync. closing	1.26	1.26	2.30	2.65
B3 switches, B1 and B2 on, 2008	1.70	1.68	5.22	6.44

Table 8 – Overvoltage and Overcurrent during Capacitor Bank Energizations

(*) pu of 230.√2/√3

Temporary overvoltages (TOV) evaluation due to the energizations, using the new criterion is shown in the Fig. 1, 2 and 3, where the limiters represent the semi-cycles limits of Table 6, converted into seconds.

In the Figure 1, we can see that the temporary overvoltage is exceeding the limiters.

Figure 2 shows the natural frequency of oscillation between the current limiting inductor and the capacitor bank (around 1.3 kHz)

With the appropriate dumping (Figure 3), the criterion (Table 7) was satisfied.

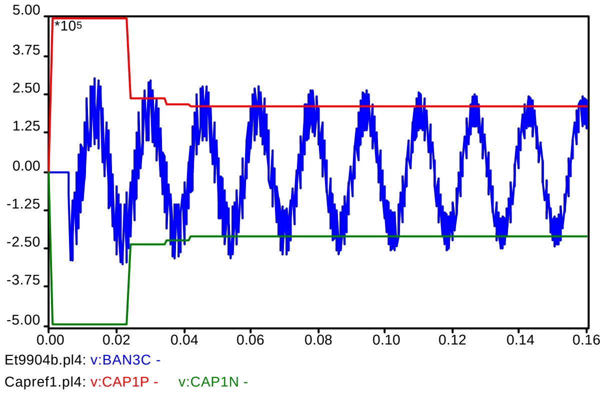

Figure 1 – Bank 3 – Energizing TOV – 1 daily switching – No inductor losses represented.

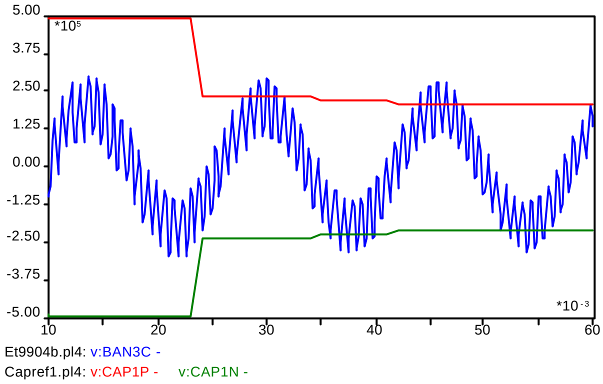

Figure 2 – Bank 3 – Energizing TOV – 1 daily switching – No inductor losses represented.

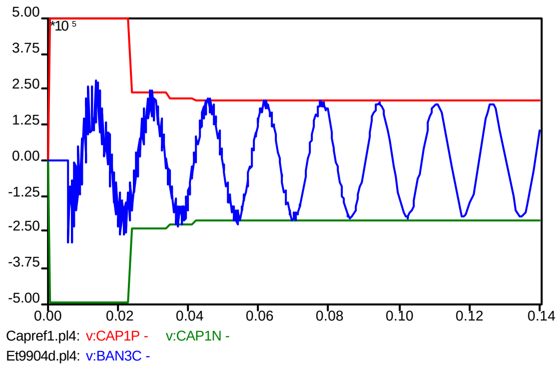

Figure 3 – Bank 3 – Energizing TOV – 1 daily switching – Inductor losses represented.

Figure 4 shows the same overvoltage of Figure 3, except that the limiters are related to 2 daily operations.

The main difference between the limiters for 1 and 2 daily operations is that the duration of each step of allowable overvoltage is lower, in the case of 2 daily (0.12 seconds against 0.24 seconds).

This type of evaluation allows us taking decisions not only on the modeling of system components but also on the number of daily switching operations.

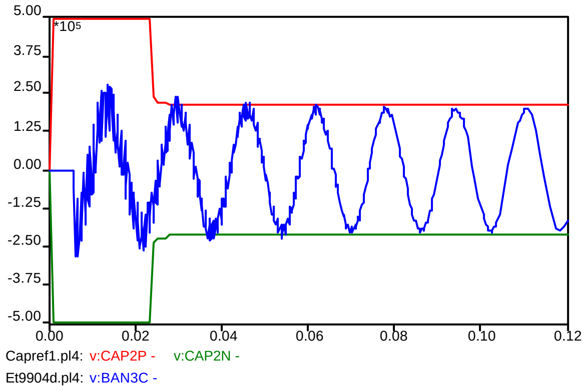

Figure 4 – Bank 3 – Energizing TOV – 2 daily switching – Inductor losses represented.

Even the effect of increasing the voltage withstand of the capacitor bank, by increasing the capacitor can voltage rating or the number of series capacitor units, can be seen through the increase of the ceiling of the limiters.

I.f products were also satisfactory for TC secondary side, during capacitor bank energizations (I.f ≤ 13.84 kA_{crest}.kHz).

4.2. Discharge of the banks on the short-circuits

For this condition, the maximum peak overcurrent in the banks was around 8.6 kA_{crest}, well below the prescribed limits (Table 6). Also, the maximum I.f product in the CT of the new banks was lower than the prescribed limit. This was achieved by using a 3 mH current limiting series inductor.

It should be mentioned that Bank 1, already in operation, didn’t have any current limiting inductor. This led to excessive overcurrent values and I.f product, which resulted in recommending a series current limiting inductor to this bank also.

4.3. Overvoltages in nearby substations

Due to the transients generated by the shunt capacitor switching on operations, significant overvoltages were observed in some of the nearby substations. This situation was observed in substations around 30 km (PA6) to 75 km (Osório) away from Gravataí substation, the last one being the most severe.

In Osório substation, the maximum line to ground overvoltage reached 2.34 pu (230.√2/√3) and the maximum phase to phase overvoltage reached 2.02 pu (230.√2).

The positive effect of the circuit-breaker control closing device was demonstrated when the Bank 1 was in its original stage, that is, with no current limiting inductor connected in series. In this case, the overvoltage was reduced to 1.64 pu.

For the phase-to-phase overvoltages, the phase combination of the voltage to ground waveforms didn’t produce the same amount of reduction observed in the case of the phase-to-ground overvoltages.

This was the case of PA6 substation, where a reduction in the phase-to-ground overvoltages around 25%, didn’t produce the same percentual reduction in the phase-to-phase overvoltages (around 2,5%).

4.4. Transient and temporary overvoltages in the system

Now, the intention was to evaluate the effect of the three capacitor banks on the system temporary overvoltages, mainly looking at stresses in the Gravataí power transformers.

Cases of load rejections in the 230 and 500 kV system, as well as fault application and clearing were simulated. Fault application cases were performed, applying three phase short-circuit in the primary side of one of the transformers inside the substation.

The fault application occurred when the instantaneous value of the phase A voltage crossed zero, opening its breaker and removing the transformer. This procedure led the remaining transformers to the saturation. Fig. 5 shows one of these cases.

Nevertheless, the temporary overvoltages (TOV) were within the prescribed limits (Item III, sub-item 4).

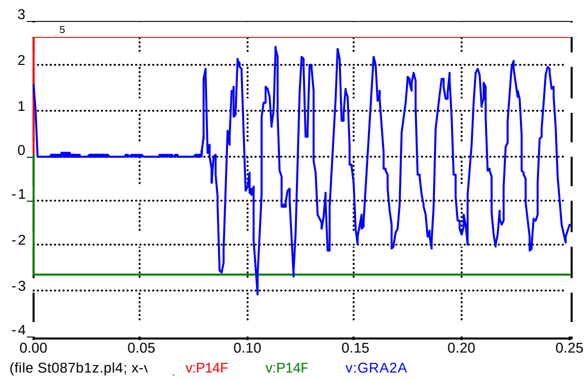

Fig. 5 – Temporary overvoltages in the substation, due to the transformer saturation.

4.5. Transient Recovery Voltages (TRV)

The aim of this study was to verify the opening conditions of the new capacitor bank circuit breakers as well as the effect of these banks on the TRV of the other circuit breakers in the substation. Short-circuit and capacitive current opening conditions were analyzed.

Concerning the maximum TRV amplitudes and its rate of rise, no problem was detected. For capacitive current opening interruption, the worst case occurred when the circuit breaker opened the sound phase (phase C), in a double line to ground fault.

Figure 6 presents the oscillogram of this case, where the circuit breaker TRV was represented by a stylized two parameters curve.

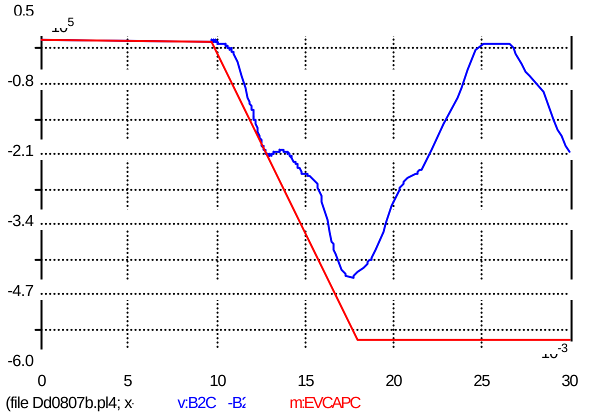

Figure 6 – Bank 2 capacitive current opening TRV, sound phase of double line to ground fault

4.6. Circuit-breaker restrike conditions on the capacitors

Restrikes occurring in one and in the three phases of the circuit breaker, during capacitive current opening, when the maximum TRV was reached, were studied.

Even for the worst case (444.8 kV_{crest}), the transient overvoltage was acceptable, if we compare it with the values of the Table 4 . On the other hand, the I.f product was exceeded in nearly 20% its acceptable limit.

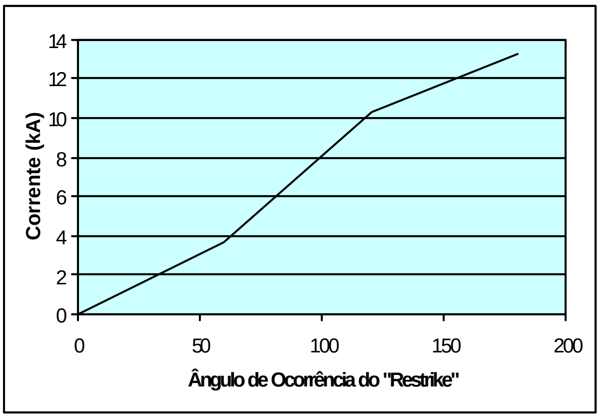

Figure 7 – First peak current versus restrike angle.

Additional simulations were performed to determine the electric angle, between 0 to 180 degrees, below which the I.f product was within the criterion.

Figure 7 shows that below 135 electrical, the first peak overcurrent will be lower than 11.17 kA_{crest}, corresponding to I.f <= 13.84 kA_{crest}.kHz.

4.8 – Lightning Overvoltages

Lightning overvoltages were evaluated to verify the current limiting inductor insulation and to check the protective effect of the capacitor bank surge arresters.

Figure 8 shows that the peak overvoltage was lower than the accepted lightning overvoltage across the inductor, equal to its BIL x 0.90 = 855 kV_{crest}.

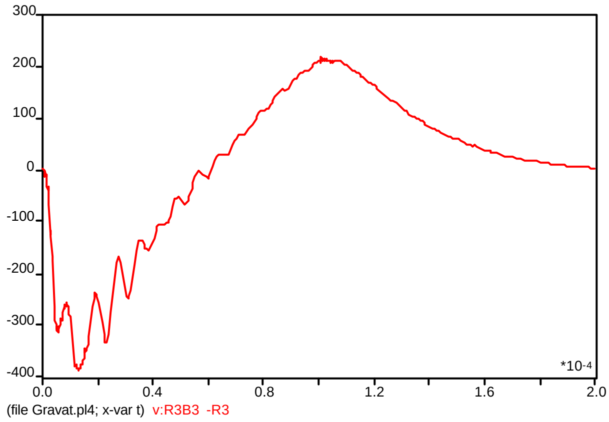

Figure 8 – Lightning overvoltages across the inductor.

V – CONCLUSIONS

A detailed study was performed for dimensioning two additional 100 MVAr/230 kV shunt capacitor banks, for Gravataí substation.

Current limiting inductors electrical characteristics as well as closing control device for the circuit breakers, were some of the important recommendations, for this new installation.

The new evaluation criteria developed, based on the standards recommendations and on the discussions with the manufacturer, allowed a more comprehensive understanding of the overvoltage and overcurrent withstand limits for the capacitor units, taking into account number of switchable shunt capacitor banks available in the substation and its policy for daily switching operations.

Some modifications in the existing shunt capacitor bank installation, like the inclusion of a current limiting inductor and a new circuit breaker with closing control device, was also recommended.

VI - REFERENCES

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