# A Comparison of the Performance of a Conventional Transmission Line and Expanded Bundle Regarding Transient Overvoltages

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**Abstract: This paper presents a comparative analysis of switching overvoltages concerning line energization, transformer energization, load rejection and three phase reclosing of a 500kV system, with three series stretches of transmission lines, under recovery conditions and considering two bundle configurations meant to be, standard dimension and expanded one. It is verified that, in general, the use of expanded bundle in these lines leads to the consequent need for a higher compensation amount of shunt reactors, and the occurrence of higher overvoltages in the phenomena analyzed, when compared with the alternative of standard bundle.**

**Keywords: Transient Overvoltages; Transmission Line; HSIL Lines; Expanded Bundle; Energization; Three Phase Reclosing; Load Rejection; No-Load Line Switching.**

## I. Introduction

Planning studies made in the Brazilian electric power system indicated reinforcements in the 500kV interconnection for the Northeast area. These analyses showed the need for installing a 500kV Transmission Line (TL) P. Dutra (PDD) - Teresina (TSD) - Sobral (SBT) - Fortaleza (FZD) and the early conversion of the two circuits on 230kV Paulo Afonso (PAF) - Milagres (MLG) – Banabuiu (BNB) – Fortaleza (FZD) into a single 500kV circuit Luiz Gonzaga (ULG) - Milagres - Quixadá (QXD) - Fortaleza. It is important to mention that these 2x230kV circuits were initially designed to be converted into a future 500kV configuration.

The operation of the first reinforcement took place in 2000 and the second circuit (conversion) was fully commissioned in 2003. The first stage of the conversion to be operated was the line between the Luiz Gonzaga power plant and the Milagres substation with step down for 230kV in this last substation, being connected to the Fortaleza substation through an autotransformer 550/230-13,8kV - 600MVA and five 230kV circuits.

The TL ULG-MLG-QXD-FZD was initially designed with a four conductors bundle configuration, in a traditional square with 18 inch (457mm) sides. This configuration was deemed a standard bundle.

Considering the construction aspects and the possibility of reducing the expected amount of series compensation to be installed on this line in the near future, the option was taken to make changes in the conception of the bundle of this line. That is, the circuit should adopt the expanded bundle solution [1,2], with line parameters similar to the TL PDD - FZD. Later on, as a result of dynamic overvoltage analyses, it was decided to develop a more appropriate bundle for the line, this being a variant of that used in the TL shown previously [3,4].

Changes in the conception of the bundle of the TL ULG-FZD and the consequent alterations in parameters L and C of the line have had as a consequence the need to reevaluate those studies in order to define the new overvoltage values due to this modification as well as to re-assess the number of shunt reactors necessary for this line.

## II. Objective

The objective of this paper is to present a comparative analysis of the transient behavior of the TL 500kV ULG - FZD, by considering the configuration of the standard bundle and that of the expanded bundle, as well as to show the changes in the compensation level that were necessary due to these modifications.

The response of the system to line energization, autotransformer energization, three phase reclosing, load rejection and no-load line opening switchings will be presented for the two conceptions studied.

## III. Description of the Electric System Studied

The Fortaleza substation was supplied originally by one 500kV circuit from P. Dutra and six 230 kV circuits, one of them originating at the Cauípe substation and the other five from the Milagres substation. From Paulo Afonso to Milagres there are three 230kV circuits and the Luiz Gonzaga power plant is connected to the Milagres substation through one 500kV circuit resulting from the conversion of the 230kV double circuit between Paulo Afonso and Milagres into a single 500kV circuit. In 2003, two of the five circuits between Milagres and Fortaleza were converted into a single 500 kV circuit, thus completing the closing of the link in 500kV between P. Dutra, Fortaleza and the Paulo Afonso

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hydroelectric power plant.

The conversion into 500kV of the line between Milagres and Fortaleza made it necessary to project and construct a substation of 500kV in Quixadá. Then, the 500 kV circuit between Milagres and Fortaleza turned out to be MLG - QXD - FZD. Figures 1 and 2 show the system studied in their two stages, the first being before the conversion to 500kV of the double circuit MLG - FZD and the second after this transformation had been made.

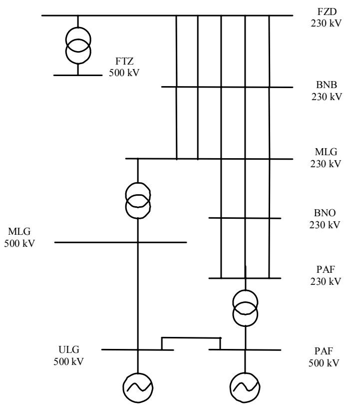


Figure 1 – System studied - 1st stage

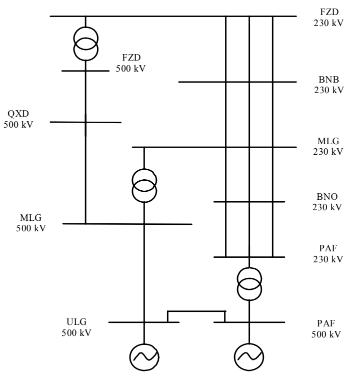


Figure 2 – System studied -2nd stage

## IV. Line Compensation Levels

As originally conceived, the 500kV line Luiz Gonzaga - Fortaleza was projected by considering a bundle of 4x636 MCM subconductors per phase with spacing between them of 457 mm, deemed the standard bundle.

Under this conception two 100 Mvar reactors in the line between ULG and MLG, one in each terminal of the circuit, two 150 Mvar reactors in the line between MLG and QXD, connected in each terminal of the line, one 100 Mvar reactor connected to the bus bar of QXD and finally one 100 Mvar reactor in the TL QXD - FZD in the terminal of this last substation would be necessary.

The application of the bundle expanded technique in the line led to a reduction of around 15% in its inductance and an increment of 20% in its capacitance in relation to the values of the line when projected with the standard bundle [3]. These changes in parameters L and C of the line resulted in the need to modify the values and the number of reactors installed in order to ensure that steady state voltages and dynamic overvoltages had compatible values with the effective planning criteria [5].

The analyses of the permanent and dynamic regimes indicated the need for one additional 100 Mvar reactor in the ULG terminal, one 100 Mvar reactor in the MLG bus bar and the replacement of the 100 Mvar reactor in the FZD terminal by another of 150 Mvar. Under these conditions there was no need for a reactor on the QXD bus bar. The total of reactors installed in the conception of the expanded bundle presents an additional amount of 150 Mvar. Illustrations 3 and 4 show the shunt compensation used in the lines between ULG and FZD for the situations under study. The parameters and the degrees of compensation of the line for both cases are presented in Table 1.

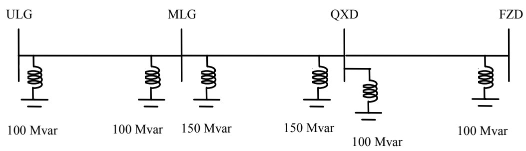


Figure 3 - Reactive compensation for the standard bundle configuration

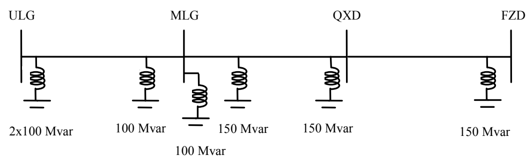


Figure 4 - Reactive compensation for the expanded bundle configuration

Table 1
Parameters and Degree of Compensation of the Ulg-Mlg-Qxd-FZD Transmission Line

| Transmission Line | Length (km) | Reactance (%) | | Susceptance (Mvar) | | Reactor (Mvar) | | Compensation degree (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Standard bundle | Expanded bundle | Standard bundle | Expanded bundle | Standard bundle | Expanded bundle | Standard bundle | Expanded bundle |
| L.Gonzaga-Milagres | 215 | 2,780 | 2,353 | 275,70 | 330,13 | 200 | 300 | 72,54 | 90,87 |
| Milagres-Quixadá | 266 | 3,410 | 2,891 | 341,02 | 409,75 | 300 | 300 | 87,97 | 73,21 |
| Quixadá-Fortaleza | 140 | 1,830 | 1,544 | 178,88 | 214,10 | 100 | 150 | 55,90 | 70,06 |

## V. Transient Analyses

The electromagnetic transient studies for the 500kV TL ULG-FZD were initially made in the TNA (Transient Network Analyzer) and in the ATP (Alternative Transients Program) program, by Chesf and Cepel staff, for the transmission line with standard bundle [6].

In view of the decision on the part of the planning and construction teams of Chesf to use expanded bundle in this line, it was necessary to reevaluate the studies already made. The changes in the level of compensation of the line and in their intrinsic parameters of inductance and capacitance would consequently lead to changes in the overvoltage levels and energy requests in the surge arresters installed in the system.

The reevaluations were made for the worst case of each phenomenon - energization, three phase reclosing and load rejection - starting from the simulations of transients with standard bundle. This prior choice of the cases to be analyzed sought to reduce the effort in the simulations and the time taken to conduct the task. The studies were made using the ATP digital program with the appropriate modeling of the system components as shown below:

- Circuit Breaker - ideal switch model;
- Shunt Reactor - branches type 98 model;
- Surge arrester - metal oxide varistor type 92 model;
- Autotransformer - transformer model;
- Transmission Line - Bergeron, transposed model.

In the following items, the results obtained for the two alternatives studied are presented.

### *A - Line Energization*

The analyses of TL energization were made in the recovery condition of the system by ULG power plant, the most severe situation.

The base voltage adopted was 550kV. The maximum voltage adopted in the bus bar where the first circuit breaker is closed before energization was 1,00 p.u..

The maximum overvoltage in the open terminal of the line was not to exceed 1,10 p.u. in the steady state condition.

The maximum switching overvoltage strength for the line was assumed to be 2,10 p.u., in accordance to switching surge insulation co-ordination studies.

### *B - Energization of the Luiz Gonzaga - Milagres line*

Table 2 presents a comparative analysis of the energization overvoltages of the TL ULG-MLG for the two conceptions studied.

Cases 1 and 2 were simulated without a surge arrester (SA) in order to show the overvoltage difference profiles in the two conceptions without its influence.

TABLE 2
TL ULG-MLG ENERGIZATION – SYSTEM IN ULG RECOVERY CONDITION

| Configuration | | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|---|
| Case | SC 1ϕ | Without reactor | Resistor (Ohm) | | $V_{máx}$ | $V_{méd}$ | $V_{máx}$ | $V_{méd}$ |
| 1 | - | - | - | ½ULG | 2,27 | 1,96 | 2,38 | 2,06 |
| | | | | MLG | 2,45 | 2,07 | 2,57 | 2,26 |
| 2 | MLG | MLG | 400 | ½ULG | 1,49 | 1,39 | 1,87 | 1,70 |
| | | | | MLG | 1,63 | 1,50 | 2,04 | 1,89 |
| 3 | MLG | - | - | ½ULG | 1,95 | 1,73 | 1,98 | 1,76 |
| | | | | MLG | 1,74 | 1,67 | 1,77 | 1,73 |
| 4 | MLG | MLG | - | ½ULG | 1,94 | 1,76 | 2,02 | 1,81 |
| | | | | MLG | 1,76 | 1,72 | 1,78 | 1,75 |

It was noticed that for the same number of reactors in the line, the overvoltage levels with expanded bundle were higher than those obtained for the line with standard bundle. In case 1, with all reactors in the line, the difference registered between the two conceptions was 5%.

Without a surge arrester and reactor in MLG terminal and with a switching resistor (resistor) in the circuit breaker of ULG, case 2, the difference between the overvoltages in the line terminal in MLG at the middle of the line was of the order of 25%. Cases 3 and 4 considered the surge arrester on both terminals of the line. Also in this situation, the overvoltages for expanded bundle were superior to those of standard bundle.

### *C - Energization of the Milagres-Quixadá Line*

Table 3 presents the energization overvoltages of the line MLG-QXD for the two line conceptions analyzed. Case 1 was simulated without surge arresters and the cases 2 and 3 were simulated with surge arresters in MLG and QXD.

Under those conditions the use of expanded bundle causes overvoltages around 9% higher than those of standard bundle, for the cases without a resistor.

With the insertion of this component, the maximum overvoltages observed were of the same order.

TABLE 3
ENERGIZATION OF THE TL MLG-QXD IN RECOVERY CONDITION FOR ULG.

| Configuration | | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|---|
| Case | SC 1ϕ | Without reactor | Resistor (Ohm) | | $V_{máx}$ | $V_{méd}$ | $V_{máx}$ | $V_{méd}$ |
| 1 | - | - | - | ½MLG | 1,99 | 1,67 | 2,17 | 2,02 |
| | | | | QXD | 2,23 | 1,81 | 2,40 | 2,20 |
| 2 | QXD | - | - | ½MLG | 1,93 | 1,67 | 2,12 | 1,89 |
| | | | | QXD | 1,75 | 1,67 | 1,79 | 1,76 |
| 3 | QXD | QXD | 400 | ½MLG | 1,95 | 1,76 | 1,96 | 1,87 |
| | | | | QXD | 1,78 | 1,72 | 1,79 | 1,76 |

### *D - Energization of the Quixadá - Fortaleza line*

Table 4 presents the energization overvoltages of the line QXD-FZD for the two line conceptions analyzed.

TABLE 4
ENERGIZATION OF THE TL QXD-FZD IN RECOVERY CONDITION FOR ULG.

| Configuration | | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|---|
| Case | SC 1ϕ | Without reactor | Resistor (Ohm) | | $V_{máx}$ | $V_{méd}$ | $V_{máx}$ | $V_{méd}$ |
| 1 | - | - | - | ½QXD | 1,91 | 1,64 | 2,05 | 1,77 |
| | | | | FZD | 2,01 | 1,70 | 2,14 | 1,84 |
| 2 | - | - | - | ½QXD | 1,80 | 1,62 | 1,89 | 1,70 |
| | | | | FZD | 1,69 | 1,60 | 1,73 | 1,67 |
| 3 | FZD | - | - | ½QXD | 1,81 | 1,65 | 1,92 | 1,73 |
| | | | | FZD | 1,71 | 1,63 | 1,76 | 1,69 |
| 4 | FZD | FZD | 400 | ½QXD | - | - | 1,86 | 1,80 |
| | | | | FZD | 1,72 | 1,70 | 1,76 | 1,74 |

Case 1 was simulated without a surge arrester in the line. For this condition, the maximum overvoltage for expanded bundle was around 6% higher than that of the case with standard bundle.

With a surge arrester in FZD, an overvoltage reduction was observed in this terminal in accordance with case 2. The overvoltage difference between expanded bundle and standard bundle in this case was 5%.

When we consider the critical case of reactor absence and a short-circuit occurrence in the FZD substation, the great effectiveness of the resistor was observed in QXD for both line configurations.

The overvoltage in FZD with expanded bundle for this situation was only 2% higher than of standard bundle, according to case 4.

*E - Energization of the Milagres autotransformer*

Energization of the 550/230-13,8kV - 600MVA autotransformer was simulated in the MLG substation in order to verify the overvoltage levels and the energy output in the surge arrester of this substation for the two bundle configurations.

As a criterion, it was assumed that the strength curve of the autotransformer supplied by the manufacturer, defined as 1,80 p.u. for 10 cycles, 1,65 p.u. for 20 cycles and 1,40 p.u. for 60 cycles, should not be exceeded nor should the maximum level of energy for the surge arrester, corresponding to 5,46 MJ, be surpassed.

The knee voltage and the air core reactance of the autotransformer were set at 1,30 p.u. and 30%, respectively, in agreement with the project data supplied by the manufacturer.

Table 5 presents the autotransformer energization overvoltages and the maximum energy level in the surge arrester for the configuration of both standard and expanded bundles.

In case 1, all reactors of the system are connected. It is observed in this situation that, for the condition of standard bundle, the overvoltage values at 10 and 60 cycles, in spite of being high, are inferior to the strength of the autotransformer.

The same occurred with the amount of energy absorbed for the surge arrester (SA energy). The overvoltage in 20 cycles is, for example, higher than that laid down in the criteria. For expanded bundle, the overvoltage levels in 20 and 60 cycles exceed the strength of the autotransformer.

The surge arrester energy levels are compatible with the criteria. In the situation of the Milagres reactor being unavailable, case 2, violation of the criteria is observed regarding the sustained overvoltages and energy in the surge arrester when the technique of expanded bundle is used. This situation presents a low reduction in the energization overvoltage of the autotransformer.

To solve these problems it is indispensable that the reactor be connected on the line in the Milagres terminal and at a level of overvoltage pre-switching lower than 1,10 p.u. in the bus bar where the autotransformer is being energized.

TABLE 5
ENERGIZATION OF THE TRANSFORMER OF MILAGRES
COMPLETE SYSTEM

| Case | Period (cycles) | Standard bundle | | | Expanded bundle | | |
|---|---|---|---|---|---|---|---|
| | | SA energy MLG | $V_{Máx}$ | $V_{Méd}$ | SA energy MLG | $V_{Máx}$ | $V_{Méd}$ |
| 1 | 0 - 10 | 3,11 | 1,74 | 1,63 | 2,30 | 1,78 | 1,73 |
| | 10 - 20 | - | 1,69 | 1,51 | - | 1,70 | 1,60 |
| | 1- 1,2 s | - | 1,24 | 1,18 | - | 1,62 | 1,39 |
| 2 | 0 - 10 | 5,03 | 1,76 | 1,66 | 6,34 | 1,81 | 1,76 |
| | 10 - 20 | - | 1,69 | 1,51 | - | 1,73 | 1,67 |
| | 1 - 1,2s | - | 1,22 | 1,19 | - | 1,70 | 1,41 |

*F - Load rejection*

Load rejection studies were made for several system situations. The most severe conditions are shown in table 6. In case 1, the values correspond to double opening of the 500 kV circuits in the MLG substation, in the recovery condition of the system for Luiz Gonzaga.

This situation corresponds to the opening of the ULG circuit breaker (CB) due to a fault to earth in this terminal with the MLG autotransformer already connected and in load condition, and the FZD CB still open.

Case 2 corresponds to the simple opening of the CB side ULG, of ULG – MLG TL. The line dropping was made 6 cycles after the fault in the ULG substation. The voltages before switching in ULG varied between 1,00 and 1,10 p.u..

Comparing the results obtained for the standard bundle with that of the expanded bundle, it is verified that the maximum and sustained overvoltages for the second configuration are 7% superior to those obtained with standard bundle. The energy levels observed [6] are inferior to the capacity of the surge arrester for both situations.

The maximum overvoltage observed for the standard bundle, under fault condition between ULG and MLG substations, was 1,91 p.u. localized ¼ from Milagres terminal. For the situation of expanded bundle, this value reaches 2,00 p.u., very close to the limit of the strength of the line, 2,10 p.u.. The maximum overvoltage between the contacts of the last CB to open was 2,44 p.u., inferior to the strength established in Standard ABNT NBR 7118 - Circuit Breakers, which corresponds to 2,80 p.u..

TABLE 6
LOAD REJECTION ON MILAGRES. RECOVERY CONDITION FOR ULG.

| Configuration | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|
| Case | Open CB | SC 1ϕ | | $V_{máx}$ / $V_{sust.}$ | $\Delta V_{máx}$ CB MLG | $V_{máx}$ / $V_{sust.}$ | $\Delta V_{máx}$ CB MLG |
| 1 | ULG MLG | ¼ULG | FZD | 1,67/ 1,19 | 2,44 | 1,72/ 1,18 | 2,43 |
| | | | ULG | 1,74 | | 1,77 | |
| | | | QXD | 1,52/ 1,20 | | 1,62/ 1,18 | |
| | | | MLG | 1,60/ 1,13 | | 1,70/ 1,11 | |
| | | | ¼ULG | 1,91 | | 2,00 | |
| 2 | ULG | - | FZD | 1,38/ 1,28 | - | 1,47/ 1,34 | - |
| | | | ULG | 1,30/ 1,22 | | 1,39/ 1,26 | |
| | | | QXD | 1,38/ 1,28 | | 1,47/ 1,34 | |
| | | | MLG | 1,29/ 1,21 | | 1,37/ 1,27 | |
| | | | ½ULG | 1,30/ 1,23 | | 1,39/ 1,27 | |

*G - Three phase reclosing*

The analyses of three phase reclosing were made for all transmission lines between ULG and FZD under fault condition in these lines and for the two bundle configurations.

*H - Three phase reclosing of the ULG-MLG line*

The three phase reclosing simulation results for the TL ULG-MLG are shown in table 7.

With all reactors connected and without a surge arrester, the maximum overvoltage in MLG, with standard bundle, is 2,36 p.u. while with expanded bundle this overvoltage reaches 2,22 p.u., according to case 1.

For the same configuration, but with a surge arrester, the maximum overvoltages for standard and expanded bundles have no difference, case 2. In case 3, the influence of the switching resistor is analyzed during three phase reclosing switching.

TABLE 7
THREE PHASE RECLOSING OF THE LINE ULG-MLG-
RECOVERY CONDITION FOR ULG

| Configuration | | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|---|
| case | SC 1ϕ | Without reactor | Resistor | | $V_{máx}$ | $V_{méd}$ | $V_{máx}$ | $V_{méd}$ |
| 1 | MLG | - | - | ½ULG | 2,17 | 1,87 | 2,00 | 1,76 |
| | | | | MLG | 2,36 | 2,05 | 2,22 | 1,92 |
| 2 | MLG | - | - | ½ULG | 2,05 | 1,76 | 1,84 | 1,64 |
| | | | | MLG | 1,77 | 1,72 | 1,76 | 1,70 |
| 3 | MLG | - | 400 | ½ULG | 1,21 | 1,12 | 1,42 | 1,36 |
| | | | | MLG | 1,32 | 1,18 | 1,50 | 1,44 |

It is observed in this condition that the overvoltages are reduced.

The overvoltages with the expanded bundle are around 17% superior to those of standard bundle.

The strength of the line to switching, 2,10 p.u., is not exceeded.

*I - Three phase reclosing of the MLG-QXD line*

Table 8 shows the results obtained in the simulation of reclosing the MLG-QXD line in recovery condition of the system starting from the Luiz Gonzaga substation.

In all cases, the overvoltages with expanded bundle are superior to those of standard bundle. For a situation without a short-circuit and without surge arrester in the line, the maximum overvoltage in the middle of this line, for the expanded bundle, reaches 23% more than that of standard bundle, according to case 1.

With a fault in Quixadá, this difference is reduced to 6% in the middle of the line and in the Quixadá bus bar it is of the same order, 1,79 p.u.. With a switching resistor, with a fault and without a reactor in Quixadá, there are no big differences in the overvoltages for the two bundle configurations, although the overvoltages of expanded bundle are slightly superior to those of standard bundle.

TABLE 8
THREE PHASE RECLOSING OF THE LINE MLG-QXD SYSTEM
IN RECOVERY FOR ULG.

| Configuration | | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|---|
| Case | SC 1ϕ | Without reactor | Resistor | | $V_{máx}$ | $V_{méd}$ | $V_{máx}$ | $V_{méd}$ |
| 1 | - | - | - | ½MLG | 1,68 | 1,56 | 2,06 | 1,89 |
| | | | | QXD | 1,68 | 1,64 | 1,80 | 1,77 |
| 2 | QXD | - | - | ½MLG | 2,03 | 1,85 | 2,15 | 1,75 |
| | | | | QXD | 1,79 | 1,75 | 1,79 | 1,73 |
| 3 | QXD | QXD | - | ½MLG | 1,95 | 1,83 | 2,08 | 1,84 |
| | | | | QXD | 1,77 | 1,74 | 1,78 | 1,75 |
| 4 | QXD | - | 400 | ½MLG | 1,75 | 1,62 | 1,90 | 1,74 |
| | | | | QXD | 1,70 | 1,63 | 1,73 | 1,70 |
| 5 | QXD | QXD | 400 | ½MLG | 1,90 | 1,81 | 1,94 | 1,86 |
| | | | | QXD | 1,75 | 1,74 | 1,78 | 1,75 |

*J - Three phase reclosing of the QXD-FZD line*

Table 9 describes the results obtained for several critical situations. In this table, it is observed that for a condition with all the reactors connected, a short - circuit in the Fortaleza terminal without a surge arrester, the maximum overvoltages in the middle of the line, for standard bundle, are 3% higher than those obtained with expanded bundle, according to case 1.

The situation with a surge arrester and without the reactor in the FZD terminal presents higher overvoltages with expanded bundle when compared with those registered for standard bundle. The biggest difference observed was 5%, case 2.

With the switching resistor, the overvoltages for the two configurations are of the same order, according to cases 3 and 4.

In both bundle configurations the overvoltages do not cause any restriction to the reclosing switching.

TABLE 9
THREE PHASE RECLOSING OF THE LINE QXD - FZD - RECOVERY CONDITION FOR ULG.

| Configuration | | | | Local | Standard bundle | | Expanded bundle | |
|---|---|---|---|---|---|---|---|---|
| case | SC 1ϕ | Without reactor | With Resistor | | $V_{máx}$ | $V_{méd}$ | $V_{máx}$ | $V_{méd}$ |
| 1 | FZD | - | - | ½QXD | 1,84 | 1,60 | 1,79 | 1,64 |
| | | | | FZD | 1,73 | 1,63 | 1,73 | 1,63 |
| 2 | FZD | FZD | - | ½QXD | 2,25 | 1,92 | 2,36 | 1,96 |
| | | | | FZD | 1,82 | 1,76 | 1,83 | 1,77 |
| 3 | FZD | FZD | 400 | ½QXD | 1,88 | 1,77 | 1,86 | 1,80 |
| | | | | FZD | 1,75 | 1,73 | 1,77 | 1,75 |
| 4 | FZD | - | 400 | ½QXD | 1,65 | 1,53 | 1,65 | 1,57 |
| | | | | FZD | 1,69 | 1,56 | 1,70 | 1,57 |

## VI. CONCLUSIONS

The change in the conception of standard bundle to expanded bundle resulted in the need to install an additional amount of 150 Mvar of shunt reactive power in the TL Luiz Gonzaga – Fortaleza.

The energization overvoltages of this line in recovery condition are, in general, greater when the technique of expanded bundle is used compared to those obtained for normal bundle. However the values of the line switching overvoltages are not exceeded (2,10 p.u.).

During the switching energization of the Milagres substation autotransformer with expanded bundle what becomes necessary is the connection of all reactors on the line. The voltage level in the MLG bus bar should be less than 1,10 p.u. in order to assure that the overvoltage will not be superior to the strength guaranteed in the over excitation curve of the autotransformer.

Load rejection in the system with expanded bundle presents higher requests for overvoltages in the substations than those obtained from the line with standard bundle. The most severe condition of line dropping showed an overvoltage between the contacts of the last circuit breaker to open of the same order for both bundle types (2,44 p.u.). This value is less than the existing one in the Brazilian Standard ABNT- NBR 7118- (2,80 p.u).

The three phase line reclosing switching for expanded bundle configuration also presents higher overvoltages than for those of normal bundle, without however being prohibitive for the line.

In conclusion, the option of expanded bundle for the TL ULG-MLG-QXD-FZD resulted in higher overvoltages during switching surge in this line when compared to those obtained with standard bundle.

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## VIII. BIOGRAPHICAL DATA

**Fernando Rodrigues Alves** was born in Campina Grande – PB - Brazil, on October 27, 1951. He graduated in Electrical Engineering from the Universidade Federal da Paraiba-UFPB - PB, in 1978; undertook a post-graduate course in Electrical Engineering Transmission Systems from the Escola Federal de Engenharia de Itajuba – MG in 1983. He received the degree of MSc in Electrical Engineering from the Universidade Federal de Itajuba – MG in 2006.
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