

**NON-CONVENTIONAL AC SOLUTIONS ADEQUATE
FOR VERY LONG DISTANCE TRANSMISSION –
AN ALTERNATIVE FOR THE AMAZON TRANSMISSION SYSTEM**

C. PORTELA *
Federal University of R. J.

J. SILVA
Damp Electric S. A.
Brazil

M. ALVIM
Furnas S. A.

SUMMARY

This paper presents non-conventional transmission systems potentially convenient to transmit large electric power, at very long distance, e.g. of the order of two to three thousand kilometers. The development of such systems was originated when searching adequate solutions for the development of Brazilian power system. The natural medium term option is to base its growth in the hydroelectric resources of Amazon basin, with moderate complementary generation based in other sources. This choice imposes an adequate solution to transmit most of such energy at distances of the order of 2500 km. The direct use of traditional solutions for typical transmission systems, developed for quite different constraints, was naturally put in doubt and it was decided to search eventually different solutions, founded in basic physical constraints, operational requirements and robust optimization and validation procedures. The main purpose of this paper is to present one of the results of the research work, namely: transmission in alternating current (AC), based in non-conventional transmission lines (LNC), with also a non-conventional conception of the transmission trunk. This type of solution was studied for applications in the medium term development of Brazilian network. So, it is presented an introduction to this network, in aspects related to long distance transmission. The main features of these examples are valid for a large spectrum of similar conditions in other countries.

KEYWORDS

Alternating current (AC), transmission system, very long distance, non-conventional transmission line (LNC), “electric length” a little longer than half wave length, null or very reduced reactive compensation, Amazon transmission system.

1 - INTRODUCTION

There are several cases around the world in which the use of very important energy resources, interesting in a strategic, economic and ambient impact point of view, imposes an adequate solution to transmit large electric power, at very long distance, e.g. of the order of two to three thousand kilometers.

As an example, the natural medium term option for the Brazilian electric sector is to base its growth in the hydroelectric resources of Amazon basin, with moderate complementary generation based in other sources. This choice imposes an adequate solution to transmit most of such energy at distances of the

* Contact author. E-mail: portelac@ism.com.br, Phone: 55-21-24934201, Fax: 55-21-24934201
Adress: Rua Eng. Cesar Grillo, 249, Rio de Janeiro, RJ, CEP 22640-150, Brazil

order of 2500 km. Similar conditions occur in other places, namely for part of important electric transmission trunks in China, India, Southeast Asia, Africa, and between Siberia and China, Siberia and South Korea, Siberia and Eastern Europe.

In order to obtain an adequate transmission system, a specific analysis must be done, with careful optimization, global, and considering a long-term point of view. It is not adequate to extrapolate solutions developed for medium distances, of the order of a few hundred kilometers.

There are two types of solutions potentially interesting:

A- Transmission in alternating current (AC) based in non-conventional transmission lines (LNC), with also a non-conventional conception of the transmission trunk.

B- Transmission in direct current (DC).

The solutions **A** and **B** are, both, essentially “point to point”, without prejudice of eventual “adaptations”, of “subsidiary” type.

It is not adequate to condition the basic conception of the transmission system, at very long distance, with other transmission aspects. For instance, the transmission at relatively short distances, of power of a lower order of magnitude, must be treated at the level of complementary networks, optimized jointly with the basic network.

The solutions **A** and **B** have quite different optimization constraints.

The correct comparison imposes a separate optimization of both solution types (**A** and **B**), and the objective and quantitative comparison of results. In some conditions, a hybrid solution may be justified.

Some recent projects have used solutions that correspond, essentially, to adapt, for very long distances, transmission trunks based in transmission lines and complementary compensation “selected” for moderate distances, of the order of 300 to 400 km, with transmission capacity, per trunk, of the order of 1 GW. They do not attain the “critical dimension” economically adequate for energy transmission at very long distance and compatible with the available generation potential for which transmission at very large distance is economically attractive. Otherwise, they did not consider a search of innovative solutions optimized for the applicable power and transmission distance.

We have done studies of non-conventional solutions, deliberately abandoning the criteria of choosing solutions similar to lines and compensation equipment of present systems, but considering very robust criteria of physical validity, ambient impact and joint global optimization of transmission trunk. Such optimization considers, namely: investment and operational costs, including losses, operational flexibility, adequacy for a large range of long-term scenarios and reliability. For instance, very interesting solutions have been obtained, based in alternating current transmission trunks, non-conventional, with unitary transmission capability from 2 GW to 12 GW, without the need of reactive compensation, or with very small reactive compensation, and without the need of intermediate substations. Such trunks can be energized and de-energized switching a single circuit breaker, with moderate switching overvoltages, have moderate losses, very good behavior for load variations and for electromechanical stability of interconnected networks, originate moderate electromagnetic field near the line, have low ambient impact and have cost typically much lower than some recent transmission systems based in conventional solutions (by example, the costs per unit of transmission capability of described trunks are of the order of one fifth to one third of the costs of recent transmission systems).

It was also done a systematic analysis for detection of potentially critical conditions of non-conventional solutions, which may be quite different of critical conditions of conventional systems. Also, were identified procedures to limit eventual undesirable constraints, adequately making use of the specific characteristics of such transmission systems.

In the paper it is presented a discussion of mentioned non-conventional solutions, with emphasis in conceptual aspects and in optimization and validation procedures. Also, as example, it will be presented an orientative range of basic parameters of such solutions, in the power and parameters range potentially interesting for transmission electric power from Amazon basin to main consumption regions of Brazil. Such examples are representative of requirements for electric transmission in other regions, as mentioned in the beginning of this introduction.

2 - INTRODUCTION TO BRAZILIAN ELECTRIC SYSTEM

In order to situate the main aspects of the Brazilian electric system, that lead to the crucial importance of very long distance transmission (of the order of 2500 km) and was the main reason to study adequate solutions for such transmission, in next future, it is presented here an introduction to the Brazilian electric system.

Brazil has an area of 8 511 968 km², 186.1 million habitants (in 2005) and a federal type political and administrative structure, with 27 “States” (including the “Federal District”, seat of federal government). There is an important diversity among several regions in what concerns population density, economic development level, climatic conditions and natural resources.

In 2005, according evaluation methodology of [1], “consumed” electric energy, in Brazil, **W**, was 373.5 TWh, including National Interconnected System – SIN (338.9 TWh), some isolated systems separated of SIN (7.2 TWh), self-generation operating almost independently of SIN, even if or when interconnected to it (27.4 TWh). The electric energy parcel classified as losses, according assumptions of [1], is not included in the amount of “consumed” electric energy indicated above.

Due to several reasons that are not dealt with here, the Brazilian growth of electricity consumption has had important changes, with a decade average annual increase (after 1970) varying between 3.7 and 12.0 % per year.

In Fig. 1 it is represented, in logarithmic scale, the time evolution of electric energy consumed, per year, in Brazil, from 1970 to 2005.

For a more detailed analysis of Brazilian electric system, it is convenient to consider some aspects of geographical distribution of population, electricity consumption and hydroelectric resources. For electricity consumption, we consider the year 2003, and an analysis based in a methodology not coincident to total electricity consumption methodology used for Fig. 1. Main difference is that most of self-generation is not included in electrical consumption of detailed analysis. Other small differences occur, namely as a result from “border” limits of “losses” excluded from consumption.

In order to clarify information relating to Brazilian “states”, a map of Brazil indicating States’ borders is presented in Fig. 2.

In Fig. 3 it is indicated [2-5]:

- The spatial distribution of population (demographic density – hab/km²).
- The electric energy consumption, per State, in 2003.

With the indicated assumptions, total electrical energy consumption, indicated in Fig. 3, in 2003, is 290.7 TWh/year.

Fig. 3 shows:

- The very irregular distribution of population, in Brazil.
- The very irregular distribution of electrical energy consumption, not only as an immediate consequence of population distribution, but also due to important differences of per capita consumption, mainly due to differences in economic development.

In Table 1 it is indicated nominal power of generation stations, according to type and situation in 13/11/2005:

- Generation stations in operation with a total nominal power 92.5 GW.
- Generation stations under construction, with a total nominal power 6.1 GW.
- Conceded (from 1998 to 2005) generation (23.7 GW), whose construction had not started, mainly due to ambient impact licensing problems.

Installed power in operation is mostly hydroelectric (76.7 %).

Brazil has very important hydroelectric resources, not yet used, and with low cost generated power. The natural option, for the near future, is to base electric generation increase, mainly, in hydroelectric power. The situation is quite different, e.g., in North America and Europe, in which most of economically competitive hydroelectric power has been implemented.

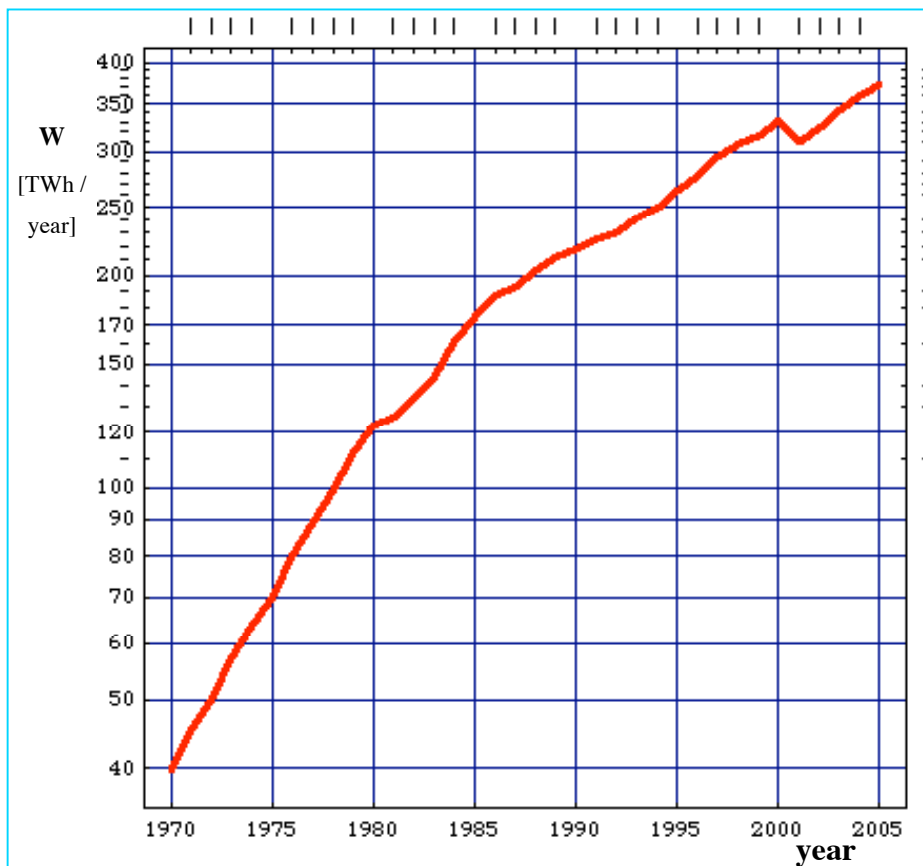


Fig. 1 – Brazilian electric energy consumption, per year, from 1970 to 2005.



Fig. 2 – Brazilian states.

Table 1 - Nominal power of generation stations, according to type and situation in 13/11/2005

Type	In operation		Under construction		Conceded, construction not yet started	
	P [MW]	%	P [MW]	%	P [MW]	%
CGH	95	0.10	0.8	0.01	36	0.15
EOL	29	0.03	208	3.42	5 642	23.80
PCH	1 316	1.42	559	9.15	3 357	14.16
SOL	0.02	0.00	-	-	-	-
UHE	69 565	75.21	3 055	49.99	5 110	21.55
UTE	19 486	21.07	2 288	37.44	9 563	40.34
UTN	2 007	2.17	-	-	-	-
Total	92 499	100	6 112	100	23 708	100

CGH Hydroelectric power station with nominal power ≤ 1 MW

EOL Aeolian power station

PCH Hydroelectric power station with nominal power > 1 MW and ≤ 30 MW

SOL Solar (photovoltaic) power station

UHE Hydroelectric power station with nominal power > 30 MW

UTE Thermoelectric power station

UTN Thermonuclear power station

However, most Brazilian hydro resources not yet implemented have some specific characteristics, very different of what is typical in North America, Europe and most of already used hydro resources in Brazil. So, it is essential to consider such specific characteristics in order to obtain adequate technical and economical solutions. The importance of these aspects justifies some discussion.

In Fig. 4 it is presented:

- Potential of hydroelectric generation, by hydrographic sub-basin and basin, referred to generation nominal power to install, according technical, ambient impact and economic criteria adopted in the inventory analysis.
- Basins installed power in March 2003.

In Fig. 5 it is presented:

- Hydrographic sub-basins installed power in March 2003.

In Table 2 it is presented a summary, indicating, by basin, the hydroelectric potential and installed nominal power (in March 2003).

Figs. 4 and 5 and Table 2 show, in a simplified way, and a more detailed analysis confirms, that:

- Brazil has a potential of hydroelectric generation of low cost and not yet used that allows, at least in order of magnitude, to triple the actual hydroelectric generation.
- The natural medium term solution, to increase electric generation, is to base such increase in additional low cost hydroelectric generation, with complementary and coordinated use, at moderate level, of other energy sources.
- Most hydroelectric resources not yet used are in Amazonian region, at large distances from main consumption centers, of the order of 2500 km.
- The transmission constraints of the electric generated power at such large distances are much different of transmission constraints in which traditional transmission systems were based.

The electric sector in Brazil has been technically advanced, in part as a result of the effort in developing technologies for the major generating and transmission systems built from 1970 till about 1995. Several of such systems involved transmission distances larger than usual, e.g., in Europe.

The positive technical attitude at the time, in Brazil, lead to several innovative solutions, in many cases contrary to typical solutions used in United States and Europe, that would be inadequate for the specific Brazilian conditions.

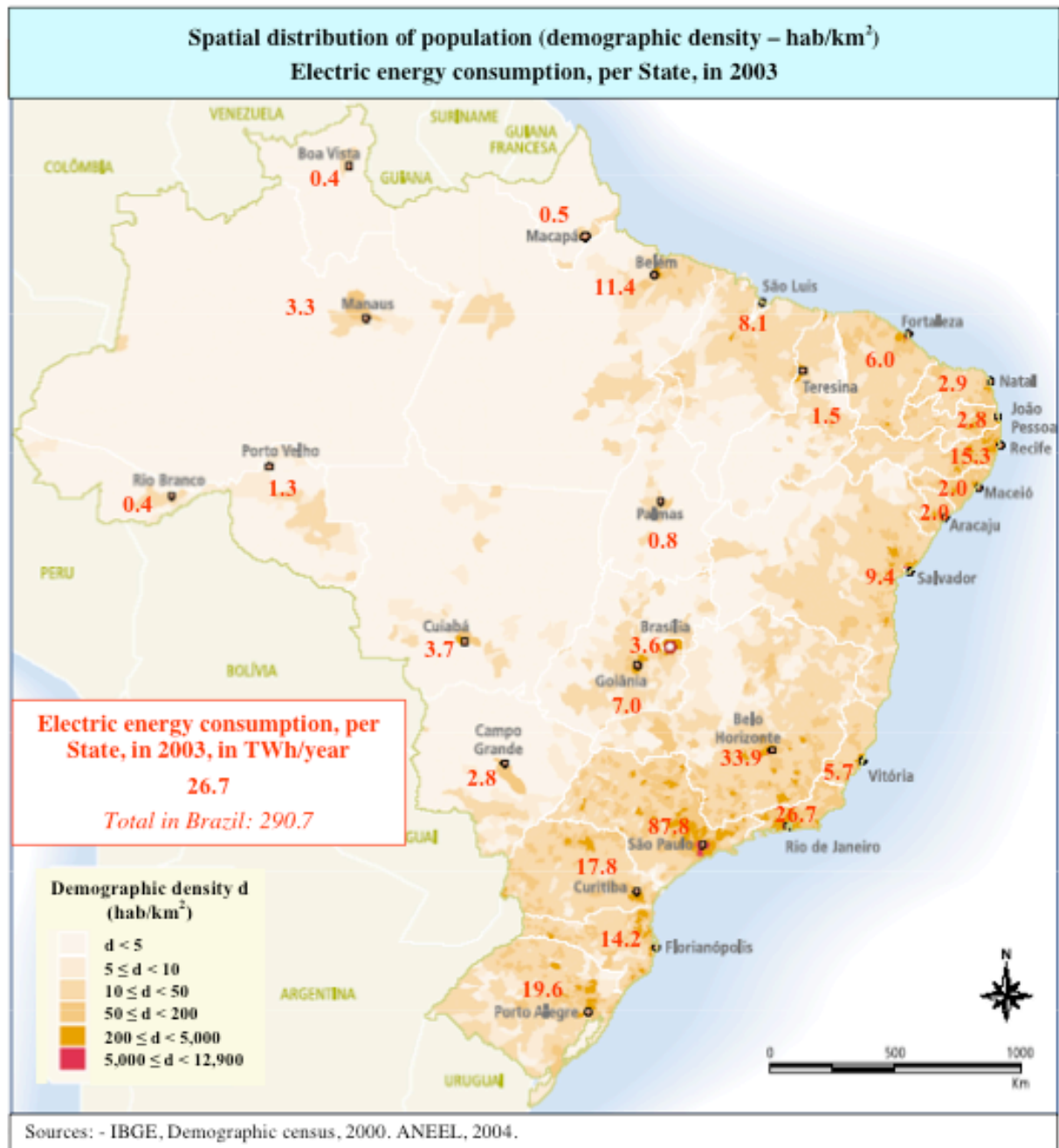


Fig. 3 - Spatial distribution of population, in 2000, and electric energy consumption, per State, in 2003.

For instance, for Itaipu system, with the transmission of about 14 GW, generated half at 60 Hz, half at 50 Hz, at 800 km distance, with several unfavourable constraints, it was necessary to develop several technologies, in a very short time, with good results.

A similar effort, in the immediate future, would be of much value in order to allow a sustained economic increase at high annual rate, for which it is essential an important growth of electrical generation with an optimised use of Amazon basin hydroelectric power.

In order clarify the main conceptual aspects of future Brazilian transmission system, adequate to the natural solution of electric generation system increase based, mainly, in hydroelectric power stations in Amazonian region, in Fig. 6 it is represented, schematically, the transmission distances between new power stations and main load centers.

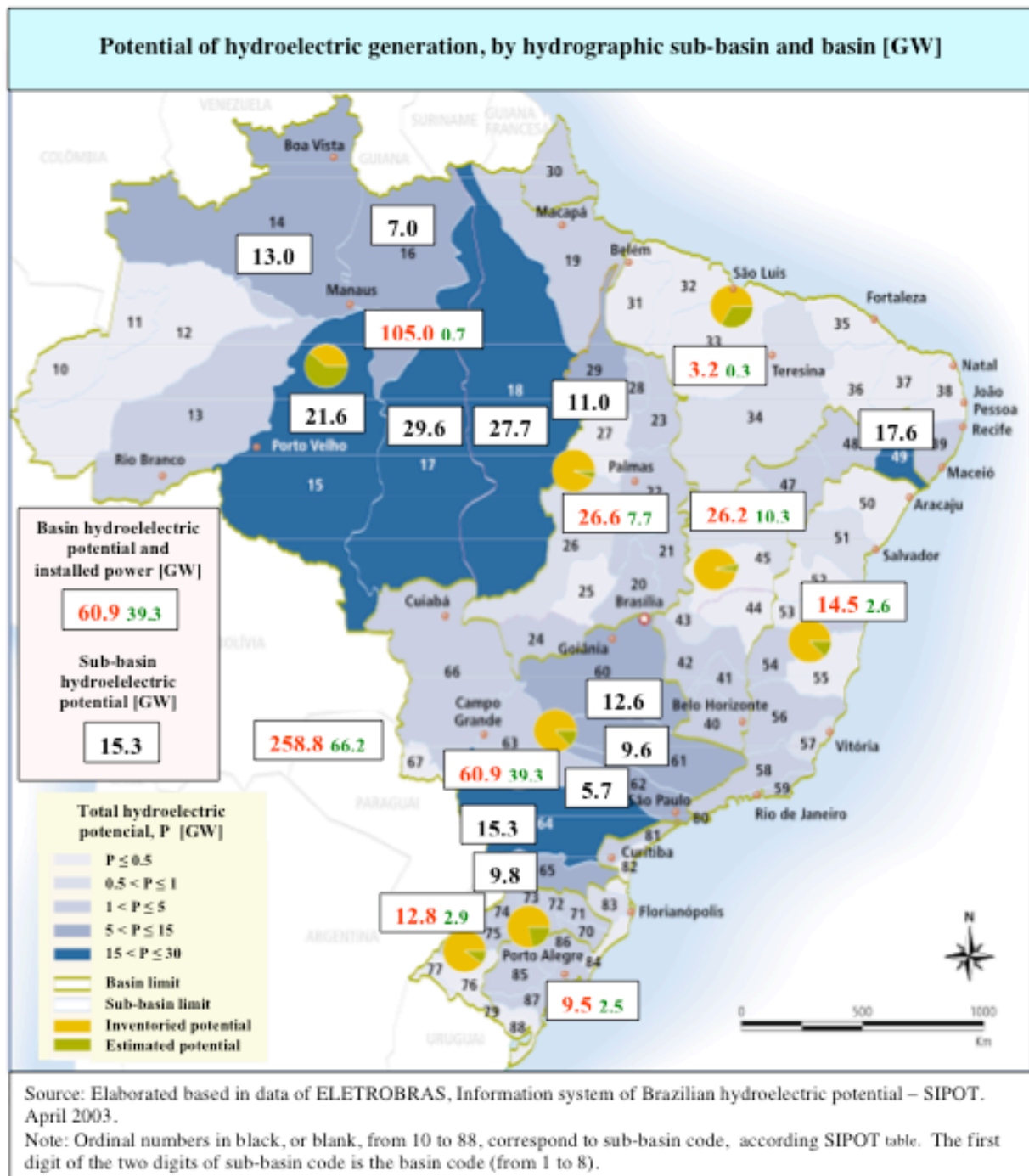


Fig. 4 - Potential of hydroelectric generation, by hydrographic sub-basin and basin, and basin installed power in March 2003.

For exemplificative purposes, we have considered, in Fig. 6:

- Three points in three of the main affluents of Amazon River, namely Xingu, Tapajós and Madeira. Potential generating powers of their hydrographic sub-basins are, respectively, 27.7 , 29.6 and 21.6 GW, according to [4].
- One “point”, or “nucleus” within the Brazilian area of higher electricity load, in São Paulo state. This approximate location is in principle adequate for receiving electrical energy through high power and large distance transmission trunks, taking into account that:
 - Electricity consumption of São Paulo state is about 30 % of Brazil total consumption.
 - Consumption of Southeast (that includes São Paulo state) and South Brazilian regions is about 70 % of Brazil total consumption.

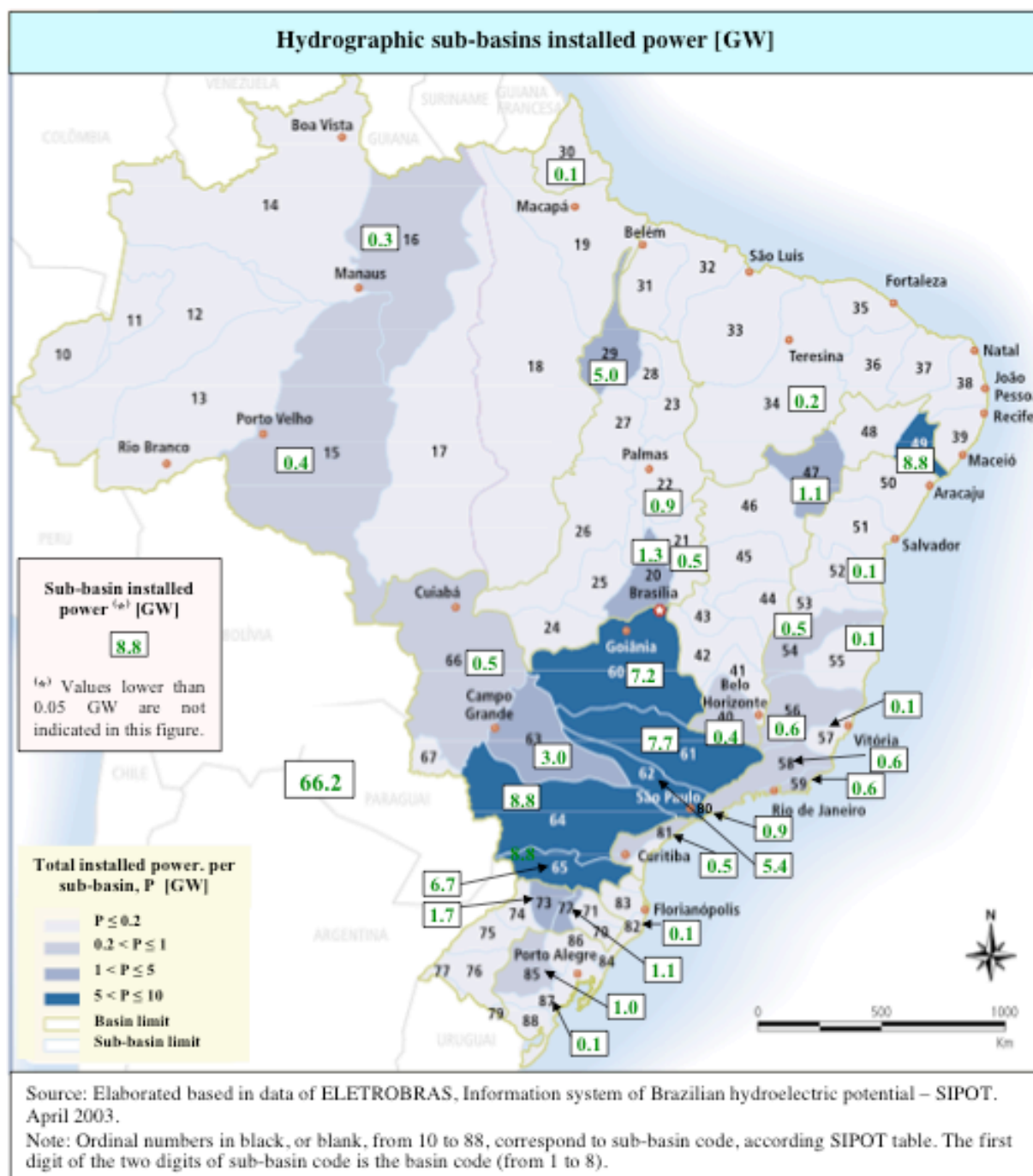


Fig. 5 - Hydrographic sub-basins installed power in March 2003.

Table 2 – Hydroelectric potential (referred to nominal power of power stations to install) and installed nominal power (in March 2003) – total and distribution by hydrographic basins

Basin	Code	Hydroelectric potential		Installed power		B/A
		A [GW]	%	B [GW]	%	
Amazonas River	1	105.0	40.6	0.7	1.0	0.63
Tocantins River	2	26.6	10.3	7.7	11.7	29.0
North/Northeast Atlantic	3	3.2	1.2	0.3	0.5	9.4
São Francisco River	4	26.2	10.1	10.3	15.5	39.2
East Atlantic	5	14.5	5.6	2.6	3.9	17.8
Paraná River	6	60.9	23.5	39.3	59.3	64.5
Uruguai River	7	12.8	5.0	2.9	4.3	22.3
Southeast Atlantic	8	9.5	3.7	2.5	3.8	26.6
Total		258.8	100	66.2	100	25.6

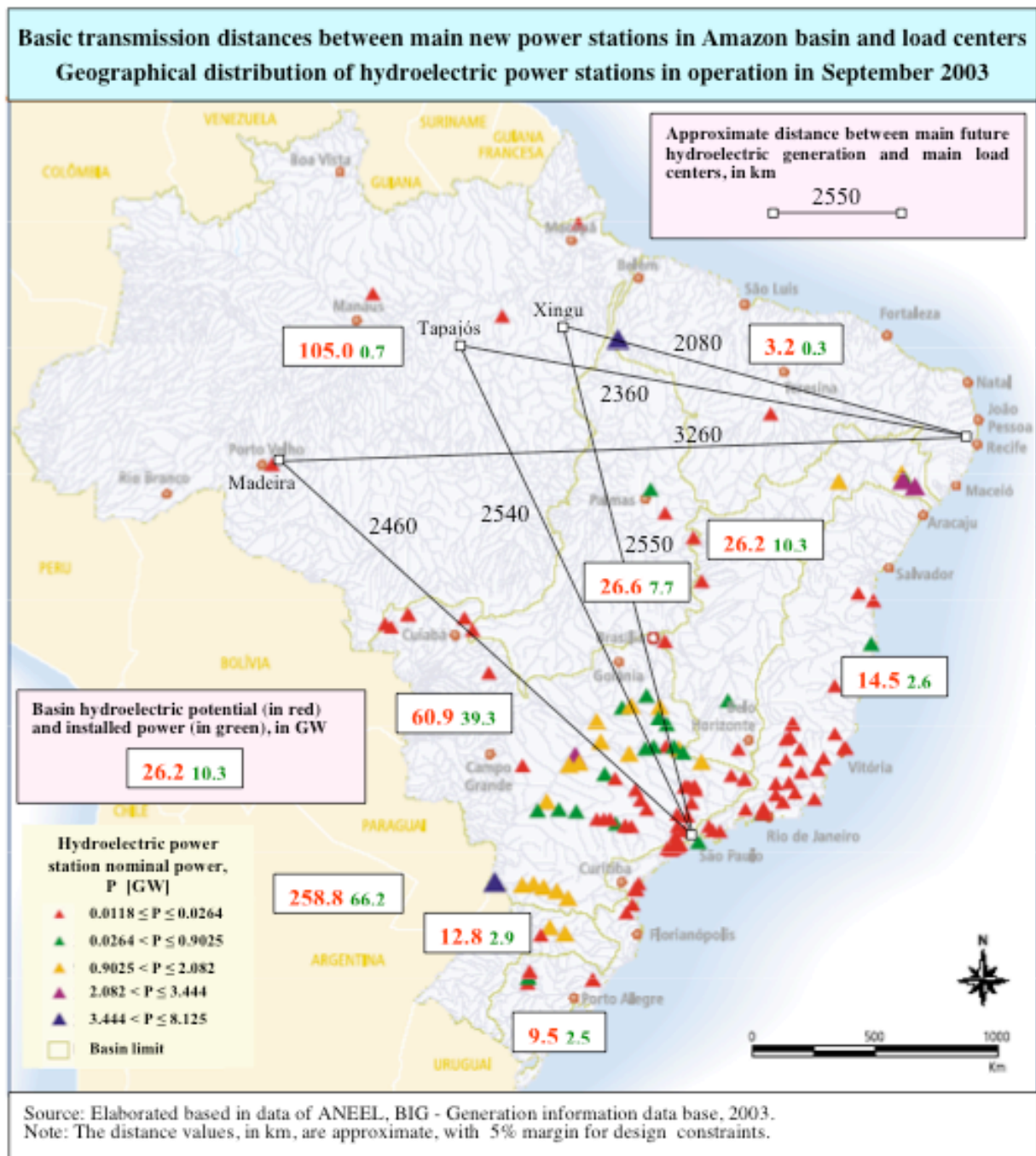


Fig. 6 - Basic transmission distances between new power stations in Amazon basin and main Brazilian load centers and geographical distribution of hydroelectric power stations in operation in September 2003.

- A large part of hydroelectric potential of Southeast and South regions is already used and it is desirable to coordinate projects related to remaining potential with large distance import from Amazonian region. This coordinated use leads to optimum design constraints different from use of remaining Southeast and South potential independent of such import, and allows a technical and economic joint optimisation of electricity consumption and generation increase.
- Southeast and South regions have an important transmission system, with AC transmission lines of 750 kV, 500 kV, 440 kV, 345 kV and 230 kV, and DC ± 600 kV transmission lines. Choosing adequately the injection “point” of large power transmission trunks from Amazonian region, the existing transmission system can be used to “transmit” imported power within Southeast and South regions, reducing major reinforcements of present transmission system.

- One “point” or “nucleus” within the Northeast region. This approximate location is also adequate, in principle, for receiving electrical energy through high power and large distance transmission trunks, although perhaps some years later than the “point” or “nucleus” in São Paulo state, taking into account that:
 - Electricity consumption of Northeast states not much far from such point is about 14 % of Brazil total consumption.
 - A large part of hydroelectric potential of Northeast region not much far from such “point” is already used and it is desirable to coordinate such potential with projects with large distance import from Amazonian region.
 - Northeast region has an important transmission system, with AC transmission lines of 500 kV and 230 kV. Choosing adequately the injection “point” or “nucleus” of large power transmission trunks from Amazonian region, the existing transmission system can be used to “transmit” imported power within Northeast region, reducing major reinforcements of present transmission system.

With the indicated assumptions, the transmission distances from Amazonian region to “Southeast point” vary between 2460 and 2550 km, and from Amazonian region to “Northeast point” vary between 2080 and 3260 km.

The viability and optimization of Amazonian hydroelectric resources impose:

- An integrated analysis of hydroelectric and transmission systems, under a long term point of view, searching solutions that adequately consider possible non-conventional solutions and scale factors for transmission lines and systems.
- Absolute precedence of rational and Cartesian criteria, avoiding the risks of pseudo-theories without agreement with physics and that confuse speculative games with economy, and avoiding the risk of thinking that:
 - Nothing different from the past makes sense.
 - To be different from the past is enough to be adequate.
- Equilibrium and rationality in the evaluation and ponderation of ecological and ambient impact constraints.

It is not within the scope of this paper to discuss in detail some transmission systems adopted in Brazil in recent years.

Also it is not the scope of this paper a systematic discussion and comparison of possible and optimized solutions for the future of Brazilian electric system.

With the objective of showing that these problems have adequate solutions, although non-conventional, it is presented, in the following item, some characteristics of a promising type of solution.

3 - A NON-CONVENTIONAL LARGE DISTANCE TRANSMISSION SYSTEM ALTERNATIVE

We present now some of the main aspects of transmission systems based in “Non-Conventional Lines” (LNC) [1], three-phase, double three-phase or six-phase, defined with basis in the following criteria:

- Do not consider restrictions that result merely of usual solutions.
- To impose only restrictions related to basic physical constraints and to performance, security and ambient impact.
- Physical parameters optimization according the specific operational functions and objectives of the line, including costs, losses, operational reliability, transmission range and operation constraints, and ambient impact, ponderated along the useful life of the transmission system and pertinent scenario range.

It was identified a set of basic physical properties that allows to choose a limited number of parameters with high correlation with several other physical, performance and cost parameters.

It is viable a robust optimization analysis, based in a moderate number of parameters and the specific constraints of the considered transmission system.

[1] – The abbreviature LNC corresponds to Latin languages order or of words (Line Non-Conventional) that where used in the first publications in which the concept of LNC was presented.

In previous work, have been defined optimization and validation methodologies, according this type of analysis [6-42].

The transmission at very large distances (of the order of 2000 km or more) has constraints much different of “usual” transmission distances (till a few hundred kilometers). So, the simple extrapolation of “usual” procedures, for very large distances, leads to inadequate or non-optimized solutions.

The defined methodologies were applied to a significant range of conditions and to a large number of examples. This analysis has allowed an approximate definition of practically feasible transmission powers, with prudent criteria, for transmission at very large distances.

Naturally, for each specific condition, it is necessary an optimization and validation analysis.

For transmission at very large distance (of the order of 2000 km or more), there are interesting solutions based, approximately, in:

- Selection of transmission trunks that behave with an “electric length” a little longer than half wave length (at power frequency).
- Point to point connection, without section switching.
- Null or very reduced reactive compensation.
- Non-conventional lines (LNC) with large transmission capability (in comparison with conventional lines).
- Joint optimization of lines, network equipment and switching and protection criteria, detecting and avoiding potentially critical conditions.

These solutions allow:

- Good performance of the transmission trunk in what concerns electromechanical stability.
- Good performance of the transmission trunk in what concerns switching overvoltages.
- Cost much lower than “traditional” solutions.
- Operational reliability much higher than “traditional” solutions.
- Ambient impact much lower than “traditional” solutions.

For these solutions, the characteristic power is, approximately, the limit of transmitted power (differently of what happens with “short” distance lines), and the conditions of maximization of characteristic power correspond also, exactly or approximately, to:

- Maximization of transmitted power limit.
- Minimization of losses.
- Minimization of corona effect.
- Maximization of viable operation voltage.
- Minimization of reactive power in several operation conditions.
- Minimization of sustained overvoltages in several operation conditions.
- Minimization of switching overvoltages for several switching operations.

We present now some results for non-conventional lines (LNC), three-phase, of voltage till 1250 kV, optimized for transmission at very large distance (of the order of 2000 km or more) [6].

In Fig. 7 it is represented the characteristic power, P_c , that can be obtained with prudent criteria, with LNC three-phase lines, in function of voltage, U_c , for voltage till 1250 kV.

In order to show some important aspects of the behavior of this type of transmission system, we present an example (Fig. 8) of a 1000 kV, 2550 km, three-phase line, with characteristic power $P_c = 8.6$ GW, without reactive compensation, switched from one extremity (all the line). Sustained overvoltage in one terminal (opened) is 1.017 pu (referred to the other terminal voltage). In Annex 1 we present a few results of other example of a 800 kV, 2550 km three-phase line, with $P_c = 4.8$ GW, without reactive compensation, also switched from one extremity (all the line). Its behavior is similar to the 1000 kV line example (in relation to the applicable characteristic power).

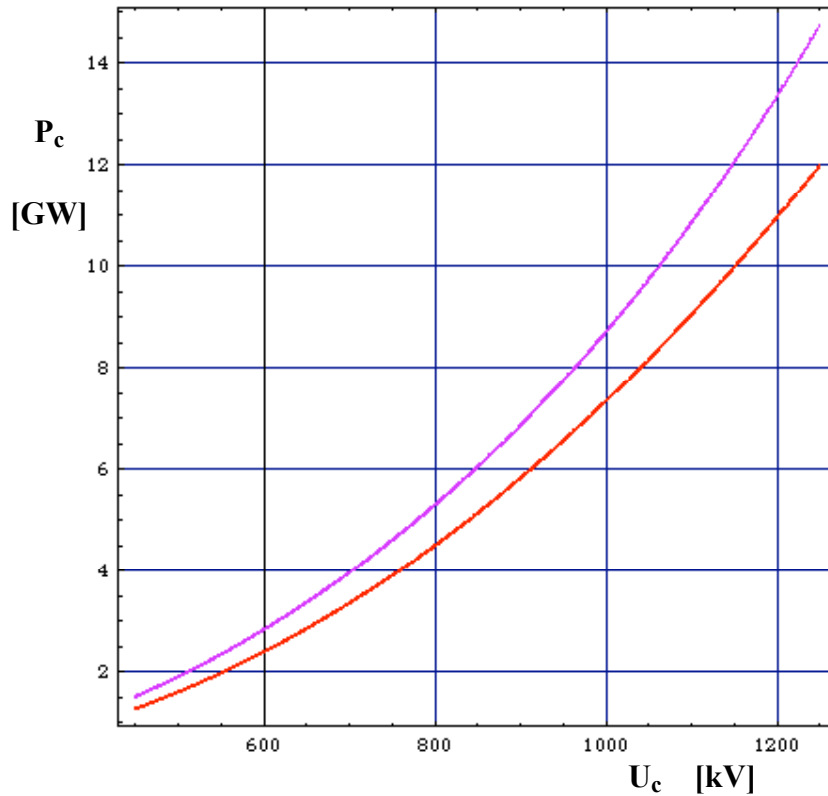


Fig. 7 - Characteristic power, P_c , that can be obtained with prudent criteria with LNC three-phase lines, in function of voltage, U_c , between phases, for voltage till 1250 kV. Curves in red and violet represent the typical range of P_c that can be obtained, depending on specific conditions and options.



Fig. 8 – Schematic representation of a 1000 kV, 2550 km, three-phase line, with characteristic power $P_c = 8.6$ GW, without reactive compensation, switched from one extremity (all the line). Sustained overvoltage in one terminal (opened) is 1.017 pu (referred to the other terminal voltage).

In Fig. 9 we represent the power, P (in GW), and the reactive power, Q (in Gvar), at line terminal 1, with voltage $U_1 = 1000$ kV, in function of phase difference, α , and ratio, R , between modules of voltages at terminals 2 and 1.

In Fig. 10 we represent line losses, p (in GW), and reactive power consumption, q (in Gvar), with voltage $U_1 = 1000$ kV, in function of α and R .

It is interesting to notice that, for this 2550 km line, the partial derivatives of P and Q in relation to $\alpha - \pi$ and in relation to module of U_2 , for module of U_1 constant, are of the type of the derivatives of P and Q in relation to α and in relation to module of U_2 , for module of U_1 constant, for a short line (of the order of 10^2 km long). So, apart an additional phase difference of π (radian), this 2550 km line has behavior quite similar to a short line, in what concerns:

- Electromechanical stabilizing effect in connection to phase shift changes of voltages at line terminals and power transfer changes.
- Voltage stabilizing effect in connection to changes of voltages at line terminals and reactive power transfer changes.

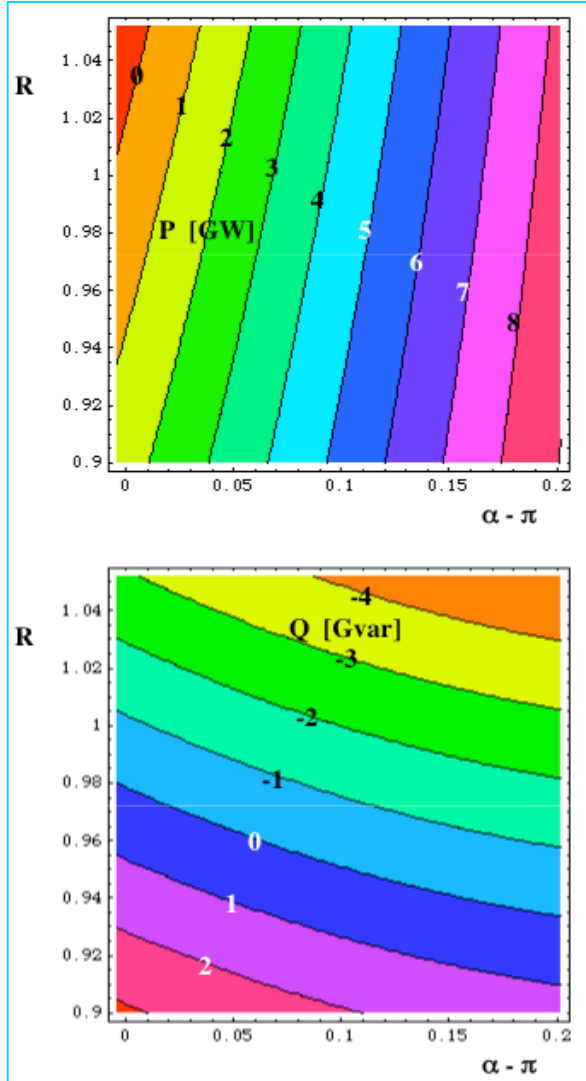


Fig. 9 – Power, P (in GW), and reactive power, Q (in Gvar), at line terminal 1, with voltage $U_1 = 1000$ kV, in function of phase difference, α , and ratio, R , between modules of voltages at terminals 2 and 1.

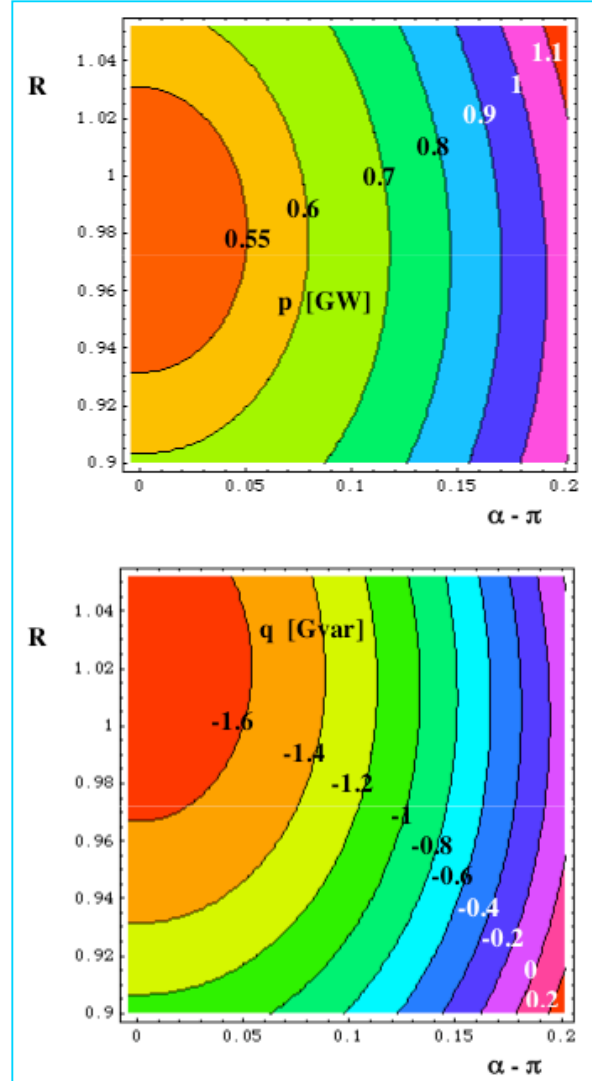


Fig. 10 – Line losses, p (in GW), and reactive power consumption, q (in Gvar), with voltage $U_1 = 1000$ kV, in function of phase difference, α , and ratio, R , between modules of voltages at terminals 2 and 1.

It is out of the scope of this paper a detailed discussion of the behavior of this type of non-conventional very long line (LNC), and, so, we present only, briefly, some important aspects.

The LNC behaves in a way similar to short lines in what concerns:

- Moderate sustained overvoltage with one terminal opened.
- Moderate switching overvoltage for connection from one terminal (all the line) with the other terminal opened.

Naturally, there are also important differences between this very long line (in the example with 2550 km) and a short line. For instance, the voltage along the line is quite sensitive to load power, and, in central line region it is approximately proportional to transmitted power. For this reason, this solution is particularly “simple” for a connection mainly “point to point” (with eventual additional connection points in vicinity of extremities, at distances of the order of 10^2 km, with some simple precautions). For other types of additional connection points, this type of solution imposes not so simple additional measures, whose discussion is out of the scope of this paper.

In Fig. 11 we present schematically the geometric position of phase cables (twelve cables per phase bundle) and ground wires, in the example line, and in Fig. 12, one of the analyzed structure types.

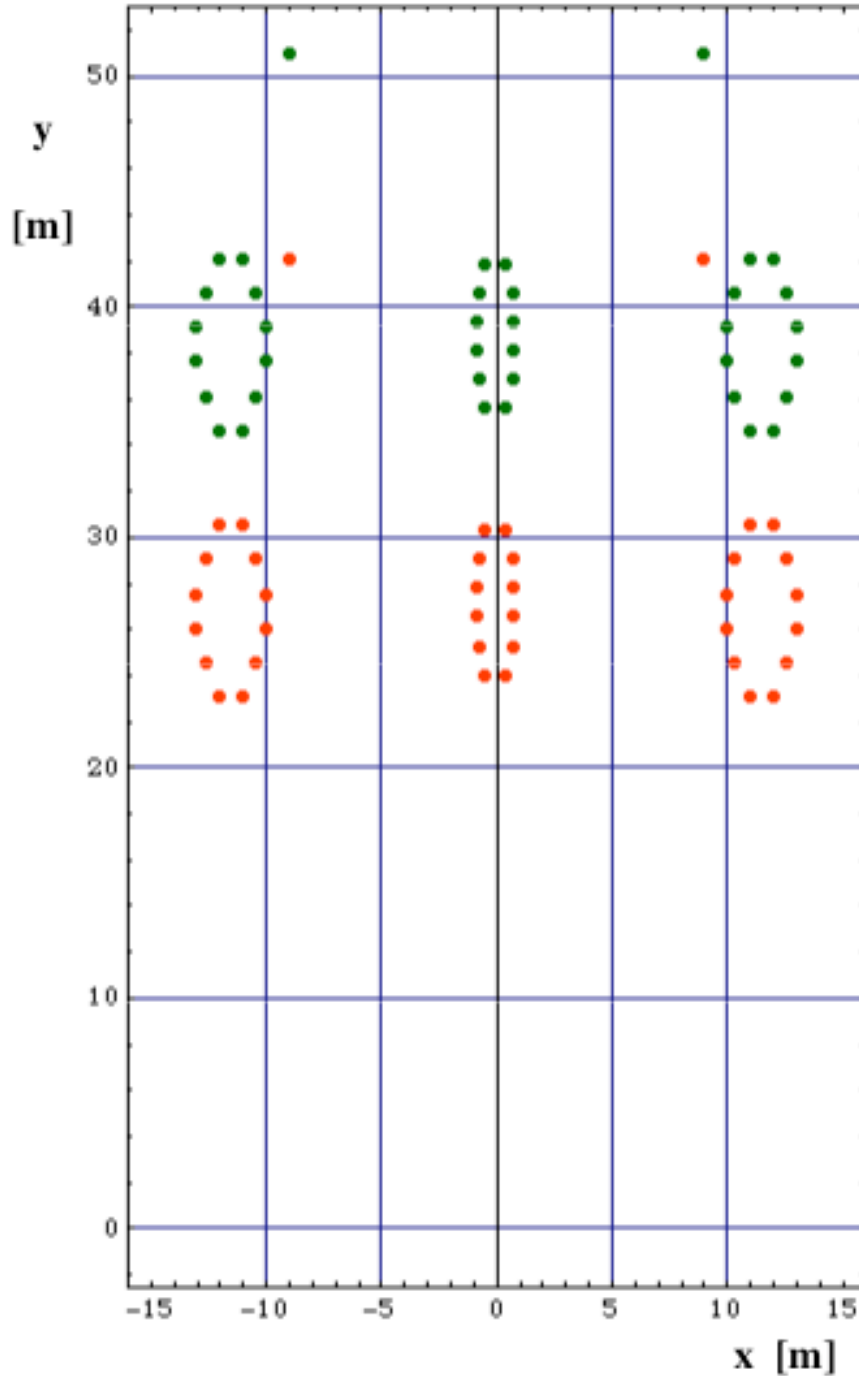


Fig. 11 – Position of phase cables (twelve cables per phase bundle) and ground wires, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, without wind. Position at mid-span is represented in red, and, near the structures, in green. Coordinate x is the algebraic horizontal distance to line's vertical symmetry plane. Coordinate y is distance to soil (assuming flat soil).

In Figs. 13 and 14 are represented, schematically, three-dimensional views of the structure of the example of Fig. 12 and of the line cables in the vicinity of the structure.

The structure of this example is formed by a horizontal beam in which are suspended the insulator chains and the ground wires, articulated to two articulated masts (also articulated in their connections to ground), and four guys. Several other types of structures have also been analyzed, with several degrees of detail. In some of them, the beam is substituted by steel cables. In others, the number of masts is increased. In others the guys are suppressed. A comparative discussion of structure alternatives is out of the scope of this paper.

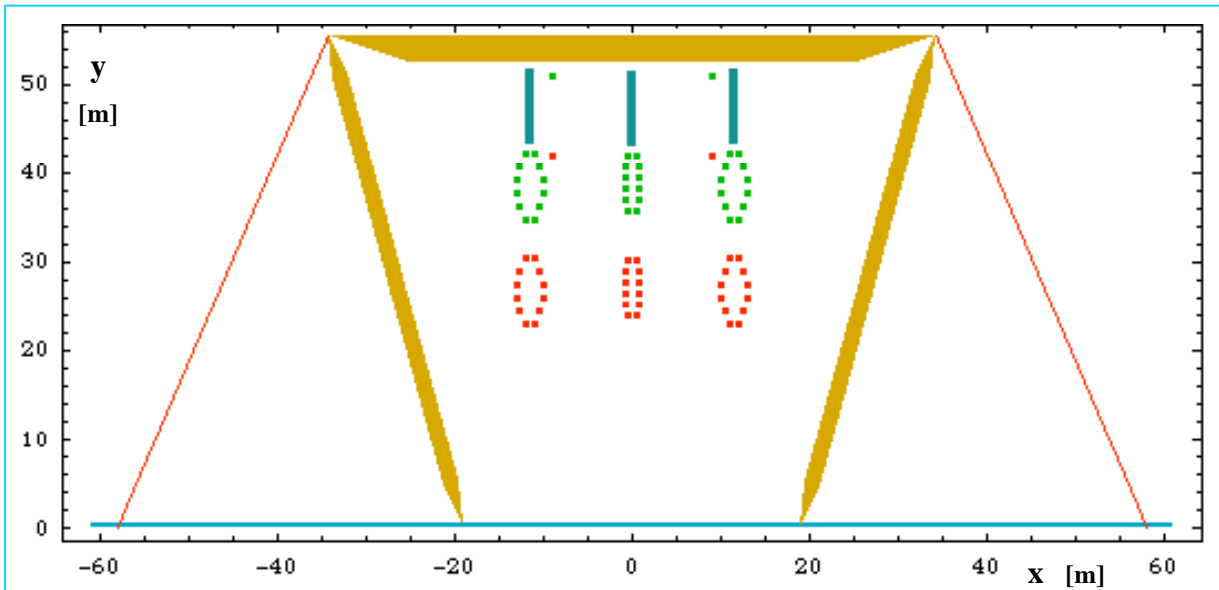


Fig. 12 – Guyed structure alternative, for example line, and position of phase cables (twelve cables per phase bundle) and ground wires, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, without wind. Position at mid-span is represented in red, and, near the structures, in green.

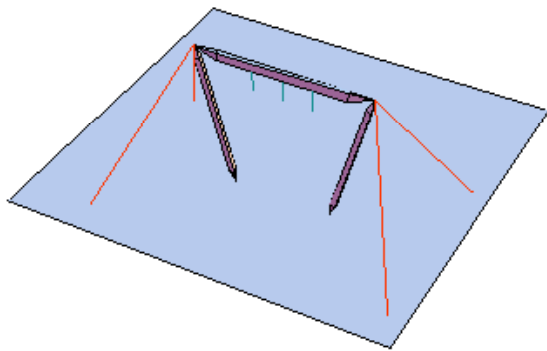


Fig. 13 – Schematic three-dimensional view of the structure of the example of Fig. 12.

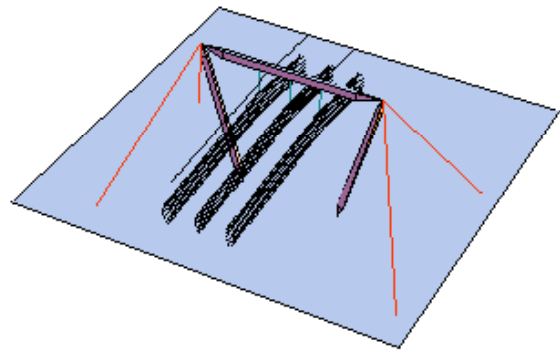


Fig. 14 – Schematic three-dimensional view of the structure of the example of Fig. 12 and of the line cables in the vicinity of the structure.

In Fig. 15 are represented, for an example of dimensions and materials of structural elements, the main parcels of compression and traction tensions of the main elements of the beam of Fig. 12.

The geometry of Fig. 12 assumes, for adequate electrical “line operation”, and according applicable conditions of insulation chains and of complementary elements (that are very important, namely in order to obtain adequate electric field three-dimensional distribution), a maximum equivalent wind speed incident in cables of the order of 110 km/h (incorporating the resultant effects of “nominal wind speed”, spatial and time wind distribution, influence of distance to ground, wind velocity exposure, gust response factor). For mechanical effects, the geometry of Fig. 12 is adequate for eventual higher wind speed, as shown in Fig. 15 in what concerns mechanical beam tension resulting from incidence of wind in conductors. The choice of structural steel material and detailed dimensions of beam elements must be chosen according applicable constraints. Also some flexibility exists in what concerns electrical “line operation”, with minor changes in beam geometry and eventual mechanical complements.

Special conditions, namely related to consequences of bundle rupture, or to guys rupture, or to effects of a structure failure in near structures, need to be analyzed according specific conditions. Basic geometry of Fig. 12 has reasonable flexibility to cope with this type of problems.

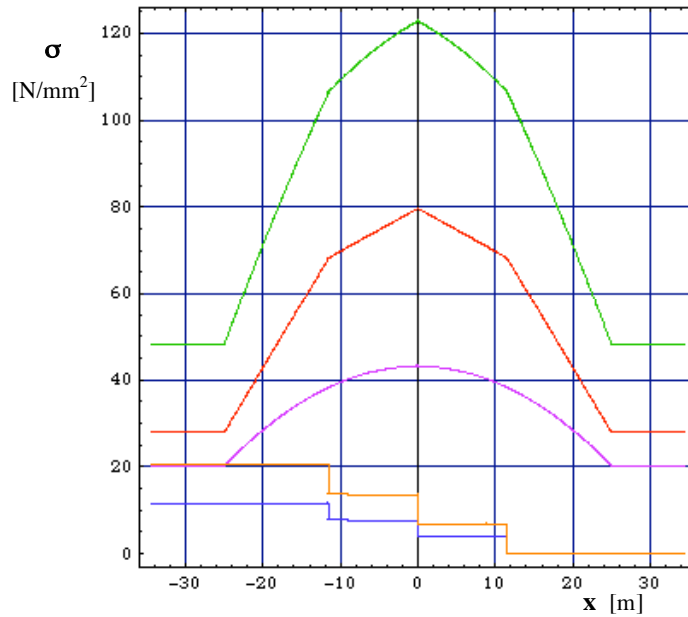


Fig. 15 – Maximum values, σ , of tension (either traction tension or compression tension) of main structural L elements of the beam of Fig. 12, in a specific example (for the involving geometry represented in Fig. 12), for horizontal soil and a span of 500 m, in function of coordinate x . Computation was done with some simplifying assumptions, whose results have a small error margin and may be a little higher than obtained with a more detailed calculation.

The curves in red and violet represent, respectively, the σ parcels associated to cables weight and to beam weight. The curve in green represents the sum of these two parcels. Except for eventual severe assumptions associated with rupture of phase bundles, these tensions represent the more important mechanical efforts in the beam.

The curves in blue and orange represent the traction tension of main structural L elements of the beam, originated by wind force in line cables, for a horizontal wind perpendicular to the line, for a speed of the wind incident in the line cables, respectively, 120 km/h and 160 km/h, in steady state.

In Figs. 16 and 17 it is indicated the electric field and the magnetic field, near the ground, at mid-span. The maximum values of both \mathbf{E} and \mathbf{H} are remarkably low, and lower than fields originated by several lines of lower voltage levels over the World.

One interesting aspect of this type of solution is the reduction of ambient impact, in comparison with traditional transmission lines. For instance:

- Soil occupation, in terms of right of way, is much smaller.
- Except for high trees, it is possible to have vegetation in the right of way area, assuring vegetation continuity. For instance, in Amazon forest, complete suppression of vegetation in the right of way zone has a considerable ecological impact, which it is important to avoid.

It is out of the scope of this paper a discussion of all aspects of the electrical and mechanical behavior of this type of solution that have been studied in order to validate it as a convenient and a potentially optimum alternative for several real conditions of long distance transmission, including the medium term new main transmission trunks adequate for Brazil electrical network expansion. So, we have chosen a few results, illustrating some important aspects of the example line behavior.

A first example refers to switching overvoltages. In order to separate and characterize the fundamental line behavior, avoiding the influence of network transient behavior and of specific soil electric parameters, chosen examples consider the line energization from an “infinite” busbar, with the opposite terminal open and with simultaneous switching on of the three phases.

Results are presented in Figs. 18, 19 and 20.

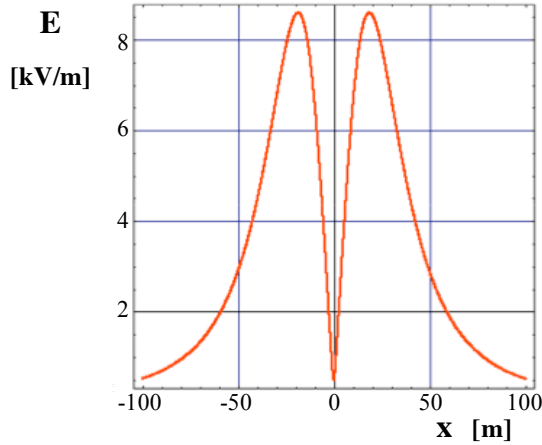


Fig. 16 – Electric field, at ground level, at mid-span, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, without wind.

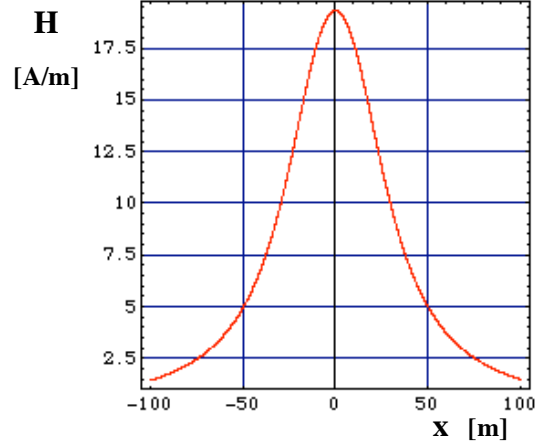


Fig. 17 – Magnetic field, at ground level, at mid-span, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, for an example of soil parameters, without wind.

In Fig. 18 it is represented the applied voltage, in one phase, u_{1a} , switched at the “infinite” busbar, at $t = 0$, and at Fig. 19, the voltage in the other line extremity, in the same phase, u_{2a} , assuming no pre-insertion resistance at the circuit breaker. Voltage is expressed in pu of phase voltage amplitude at the infinite busbar. In Fig. 20 it is represented the voltage u_{2a} , in similar assumptions, but using a pre-insertion resistor.

This example shows that it is obtained a remarkable low value of switching overvoltage, energizing the 2550 kV line with a very simple switching procedure, in a single step.

A second example refers to the possibility of assuring a high probability of extinction of a fault current between a phase of the line and ground (or a point of the line connected to ground, e. g. a line structure or a line ground wire), within a reasonably short time, without disconnection of healthy phases and allowing reclosure of faulty phase after arc extinction.

At least in regions of high lightning incidence, as it is the case of most Brazilian territory, the large majority of line faults are single phase faults originated by lightning, with formation of an arc in air, between a phase and a grounded line element, namely a line structure or a ground wire. If it assured a high probability of successful elimination of the “secondary arc” (arc in air at fault point after opening of faulted phase at both line extremities, maintaining closed the other two line phases), and successful reclosure of faulted phase, in a reasonably short time, the disturbance for the network is quite moderate. Otherwise, the fault imposes the three phase line opening and subsequent reclosure, what is more severe for the network, specially if the network does not allow the automatic transfer of the power transmitted by the line affected by the fault for other lines.

In the common conditions of relatively short lines (length till a few hundred kilometers) this problem is frequently solved by an adequate parameters’ choice of compensating reactors at line extremities.

Choosing correctly the power frequency parameters of such reactors, including an eventual additional reactor between neutral point of phase reactors and ground, and disconnecting the faulted phase at both terminals, it occurs a reduction of arc current at fault point, and a reduction of recovery voltage after arc extinction. In principle, this procedure allows the fault elimination, and the subsequent successful reclosure of faulted phase, without interruption of the other two phases.

To evaluate correctly and with small error margin the required conditions for effective extinction of secondary arc, it must be taken into account:

- The non-linear arc behavior, modeled with acceptable accuracy, for slow and fast phenomena.
- Dynamic interaction between the arc and the network, in a large frequency spectrum.
- The arc length time variation due to wind and thermal convection and including effects of turbulence type phenomena in arc plasma and in air.

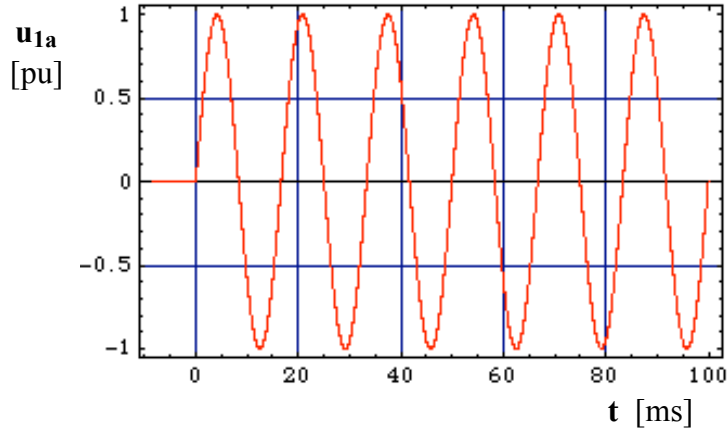


Fig. 18 – Applied voltage, in one phase, u_{1a} , switched in terminal 1 at the “infinite” busbar, at $t = 0$, in pu of phase voltage amplitude at the infinite busbar, \hat{U} .

For the nominal voltage 1 MV at the busbar it is

$$\hat{U} = \sqrt{2/3} \cdot 1 \text{ MV} = 816.5 \text{ kV}.$$

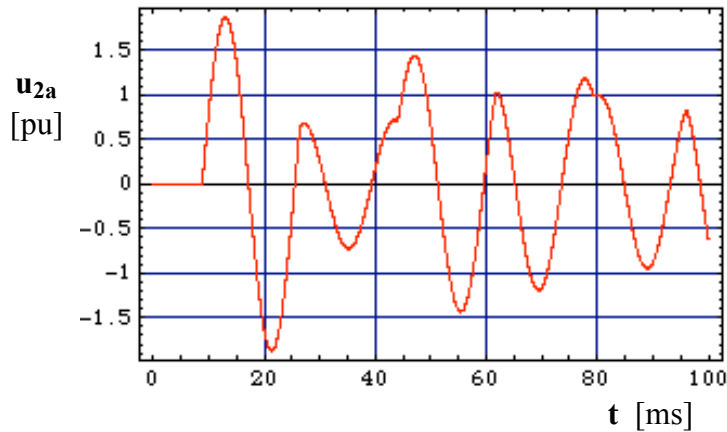


Fig. 19 – Transient voltage, u_{2a} , in the same phase, in the other line extremity, in the same phase, with no pre-insertion resistor at the circuit breaker, and without surge arresters at terminal 2. Peak value of $|u_{2a}|$ is 1.88 pu. Power frequency voltage amplitude at terminal 2, with no load, is 1.017 by the voltage amplitude at terminal 1.

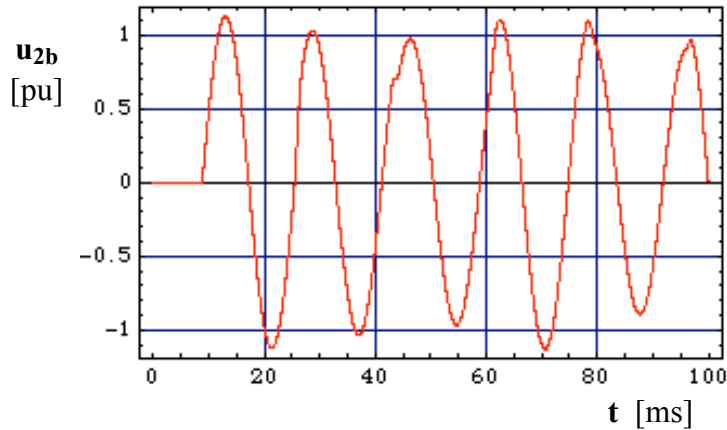


Fig. 20 – Transient voltage, u_{2b} , in the same phase, in the other line extremity, in the same phase, with a pre-insertion resistor of 77.5Ω in the switching circuit breaker, connected during 1 cycle (16.7 ms). Peak value of $|u_{2b}|$ is 1.13 pu (923 kV for nominal voltage at terminal 1). Power frequency voltage amplitude at terminal 2, with no load, is 1.017 by the voltage amplitude at terminal 1.

For the nominal voltage 1 MV at the busbar, the energy dissipated in the pre-insertion resistor is 11.5 MJ.

For relatively short lines, in which it is easy to assure very low fault current and very low recovery voltage, it may be acceptable to consider a simplified procedure to “assure” secondary arc extinction, with simplified assumptions about arc modeling, what implies an high error margin in the evaluation of the required limit conditions for effective extinction of secondary arc.

For very long lines, with null or small reactive compensation, the procedure indicated above, used for relatively short lines, and the eventual simplifying assumptions indicated above, are not adequate.

It is necessary to choose different procedures to obtain high probability of secondary arc extinction, considering the specific characteristics of the long lines and a reasonable accurate arc modeling.

It is important to assure the possibility of single phase opening and reclosing, in case of single-phase faults, in very long lines and transmission trunks, of the type presented in this paper. It is not viable to present in detail, within the scope of this article, methodologies to study and define procedures to assure high probability of secondary arc extinction. So, we only discuss some basic aspects of secondary arc extinction, and present some simulation results, in very simple assumptions. The example conditions were chosen in order to emphasize line aspects, avoiding possible important influence of example peculiarities not related to line and transmission trunk.

It was considered that the chosen transmission line was connected to two infinite busbars with balanced voltage 1000 kV , 60 Hz , with a phase difference α . It was chosen a point P along the line with unfavorable behavior in what concerns phase-ground short-circuit (neglecting arc voltage). I , and recovery voltage, U , both expressed by sustained power frequency component, and indicated in graphics by their *rms* value.

In Fig. 21 it is represented I and U , in function of α , with the line connected to infinite busbars in the three phases. Independently of arc detailed modeling, it is easily concluded that, in this conditions, the arc fault has not a significant probability of extinction, in a reasonably short time.

In Fig. 22 it is represented I and U , in function of α , with the circuit breakers of both line extremities open in the fault phase and connected in the other phases. Both I and U are much lower than in conditions of Fig. 21 , but are still too high to assure a significant probability of arc extinction, in a reasonably short time. However, it is possible that there is a non-negligible probability of arc extinction, but with an excessive arc duration, in the relevant system behavior aspects affected by such duration.

In Fig. 23 it is represented I and U , in function of α , with the line extremities disconnected, in the fault phase, from the busbars, and connected to auxiliary circuits for arc extinction, and with the two other phases connected to the busbars. In this example, the auxiliary circuits, of FACTS (“*flexible AC transmission system*”) concept, act as voltage-current sources at the line extremities of the fault phase. Its control parameters are defined from fault location, as determined by line protection system, and from voltages and currents in the line extremity in which the auxiliary system is installed. Both I and U are quite low and certainly assure a high probability of arc extinction, in a short time. This shows that it is feasible to obtain extinction of secondary arc for the transmission trunk of 2550 km presented in this paper as example. However, the results obtained in the conditions of Fig. 23 show unnecessary low values of I and U . This fact indicates that, possibly, the auxiliary systems for arc extinction considered for Fig. 23 results are not fully optimized and simpler solutions can probably be adopted.

A simpler solution for the auxiliary systems for arc extinction has been found. It considers the physical behavior of arc and its interaction with the network as seen at arc terminals, and is based in auxiliary systems that act as voltage-current sources at line extremities of fault phase. Such systems are not based, mainly, in power frequency effects. The discussion of this type of solution would involve several aspects different of those presented above and is outside the scope of this paper.

We must clarify that, in the presented results and examples, several precautions have been taken in order to reduce the risk of collateral effects in aspects that were not evaluated with the systematic precautions considered necessary for validation. For some of such precautions, we consider that there is a high probability that a more complete validation analysis will show that some of the adopted precautions can be at least relaxed, in a quantitative sense. If this possibility will be confirmed, additional advantages can be obtained with the presented solution for long distance transmission. It would be enough to change the precaution limits, maintaining the same methodology. We present, briefly, two examples.

One example relates to the symmetry constraints of phase bundles, that was adopted to reduce mechanical problems risks associated with vibration modes and wind effects related with mechanical accessories of insulator chains and its connections to bundles, bundle spacers and dampers. Although the problems to deal with present no special difficulty, some of them may be not covered by traditional project, specification and test procedures. So, such problems must be examined with some care.

A preliminary evaluation shows that the elimination of symmetry constraints, with maintenance of bundle overall approximate limits and some other constraints, would allow a few percent increase of the characteristic line power (that defines the limit of transmitted power at very long distance) and a few

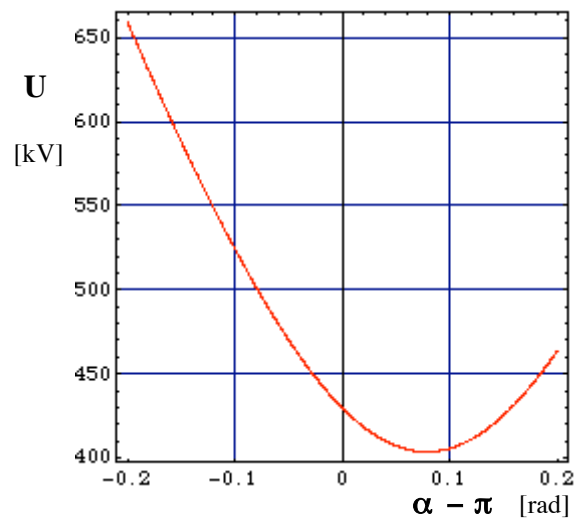
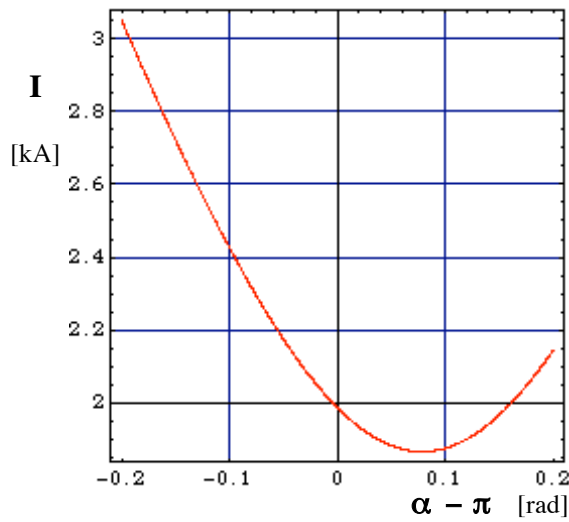


Fig. 21 - Single phase short-circuit at line point P , phase **a**. Circuit breakers closed, in all phases, at both line extremities.

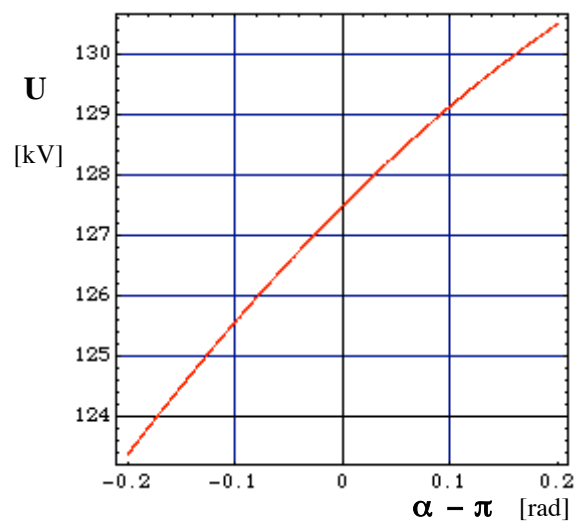
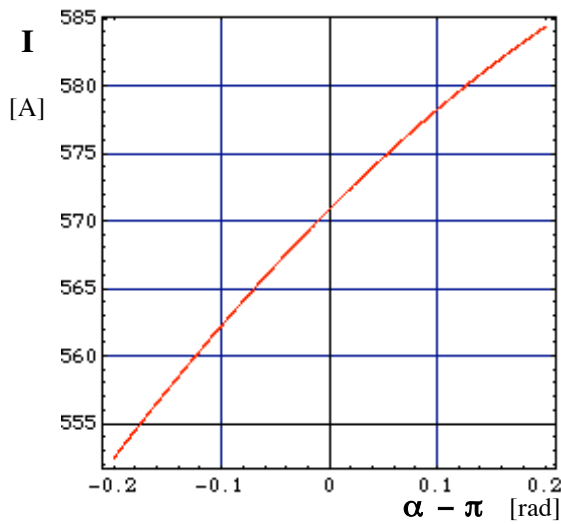


Fig. 22 - Single phase short-circuit at line point P , phase **a**. Circuit breakers open, in phase **a**, at both line extremities, and closed at the other two phases.

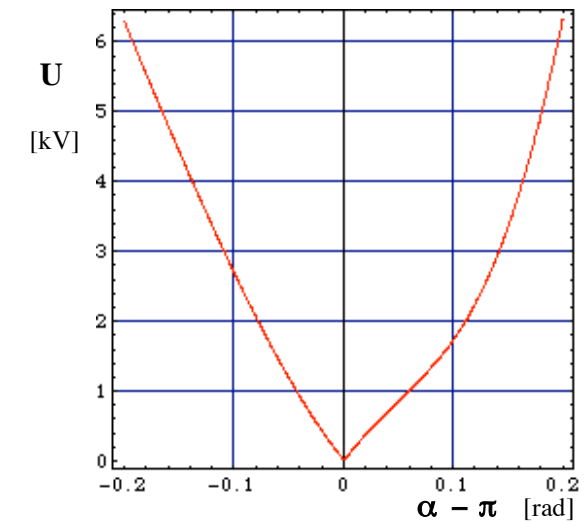
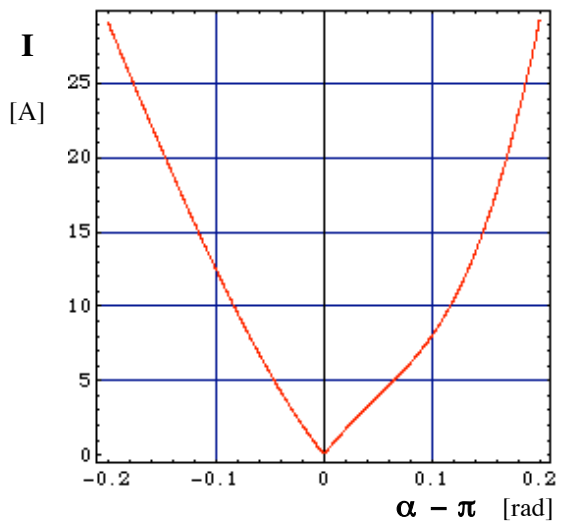


Fig. 23 - Single phase short-circuit at line point P , phase **a**. Circuit breakers open, in phase **a**, at both line extremities. Auxiliary circuits for secondary arc extinction connected, in phase **a**, at both line extremities.

percent reduction of line losses, practically with no increase of line cost. So, it is justified to study, with due care, the eventual measures and precautions adequate for validation of changes indicated above about symmetry constraints.

The other example is related to the type of cables. In the presented examples we have considered, for phase bundles, the “traditional” aluminum cable steel reinforced cables, chosen within usual international series. There are some special series that may have some advantages. For instance, cables based in trapezoidal wires or in Z shaped wires, and cables using other materials or with an external surface of special shape, e.g. with tracks. In principle, the methodology used applies to any type of cables. Naturally, it is necessary to consider the effective characteristics of each type, for the several electrical, thermal and mechanical (including wind effects) aspects that affect line behavior, constraints and requirements, including influence in other line elements and joint optimization.

One aspect that may be interesting is the possible use of cables using trapezoidal or Z shape wires, or of special external shape. The possible reduction of wind force, in relation to conventional cables, may imply in a significant reduction of conductors and insulators balance and a significant reduction of longitudinal forces in cables and of horizontal forces in structures. In principle, it is convenient some validation analysis about some problems frequently not well evaluated in relation to vibration and damping behavior and interaction with spacers and dampers. Also some cost evaluation is convenient when using less common cable types.

We present now some brief comments about cost aspects of the non-conventional transmission systems presented in this paper.

The indication of absolute specific costs, in a general context, would have a large error margin, due to the many aspects that affect “expressed” cost, and are, in great part, independent of effective technical cost in an objective set of clear conditions. So, we will present only some approximate relative costs taking as a basis some recent projects of transmission trunks of about 1000 km , 1 GW maximum transmitted power, based in “conventional” transmission systems for lengths of the order of a few hundred kilometers, and that implied in massive reactive compensation in the transmission trunk and in the connected networks. It is out of the scope of this paper to discuss such projects, which are referred only because they were object of recent options and decisions, and correspond to what was the reality in a specific context.

For this comparison we consider as “unity cost” the “technical cost” of a line (Case a), with 2550 km , similar to a concrete line of a relatively recent project, 500 kV , 1 GW , excluding intermediate substations and reactive compensation along the line and in the interconnected networks to allow line operation. Its cost was decomposed in the representative parcels, from which, in a technical basis, the corresponding costs of the example line, presented above (Case b), with 2550 km , 1000 kV , 8.6 GW , were estimated, assuming identical cost criteria. The result is indicated in Table 3.

Table 3 – Cost comparison of: - A transmission system similar to a recent project based in conventional systems (Case a). - The presented example of a non-conventional transmission system (Case b).					
Cost parcel	Total costs, C		Relative costs, $c = C / P$		c_b / c_a
	C_a (Case a)	C_b (Case b)	c_a (Case a)	c_b (Case b)	
	P = 1 GW	P = 8.6 GW	P = 1 GW	P = 8.6 GW	
C_1	1.00	2.56	1.00	0.298	0.298
C_2	0.70	0.00	0.70	0.000	0.000
$C_t = C_1 + C_2$	1.70	2.56	1.70	0.298	0.175

C_1 Line cost, excluding intermediate substations and reactive compensation along the line and in the interconnected networks to allow line operation.
 C_2 Cost of intermediate substations and reactive compensation along the line, and in the interconnected networks, to allow line operation.

In the assumptions of Table 3:

- The total cost of the presented example, with a transmission capacity of 8.6 GW, at 2550 km, is only about 51 % higher than the total cost of a transmission system with a transmission capacity of 1 GW similar to a recent system based in conventional solutions (for the same line length in compared costs).
- The relative cost (per unit of power transmission capability, and for the same line length) of the presented example:
 - Is about 30 % of the line cost of the comparison case based in conventional solutions (excluding intermediate substations and reactive compensation along the line, and in the interconnected networks, to allow line operation).
 - Is about 18 % of the cost of the comparison case based in conventional solutions (including intermediate substations and reactive compensation along the line and in the interconnected networks to allow line operation).

Anyhow, the non-conventional solution presented in this paper allows transmission costs at large distances (of the order of 2000 to 3000 km) much lower than AC transmission systems based in solutions developed for traditional transmission systems, for distances of a few hundred kilometers.

4 - CONCLUSIONS

There are several cases around the world in which the use of very important energy resources, interesting in a strategic, economic and ambient impact point of view, imposes an adequate solution to transmit large electric power, at very long distance, e.g. of the order of two to three thousand kilometers.

An example is the natural medium term option for the Brazilian electric sector, described in the paper, that imposes an adequate solution to transmit most of its energy generation increase at distances of the order of 2500 km. Similar conditions occur in other places, namely for part of important electric transmission trunks in China, India, Southeast Asia, Africa, and between Siberia and China, Siberia and South Korea, Siberia and Eastern Europe.

In order to obtain an adequate transmission system, a specific analysis must be done, with careful optimization, global, and considering a long-term point of view. It is not adequate to extrapolate solutions developed for medium distances, of the order of a few hundred kilometers.

There are two types of solutions potentially interesting:

A- Transmission in alternating current (AC) based in non-conventional transmission lines (LNC), with also a non-conventional conception of the transmission trunk.

B- Transmission in direct current (DC).

The solutions **A** and **B** are, both, essentially “point to point”, without prejudice of eventual “adaptations”, of “subsidiary” type.

It is not adequate to condition the basic conception of the transmission system, at very long distance, with other transmission aspects. For instance, the transmission at relatively short distances, of power of a lower order of magnitude, must be treated at the level of complementary networks, optimized jointly with the basic network.

The solutions **A** and **B** have quite different optimization constraints.

The correct comparison imposes a separate optimization of both solution types (**A** and **B**), and the objective and quantitative comparison of results. In some conditions a hybrid solution may be justified.

Some recent projects have used solutions that correspond, essentially, to adapt, for very long distances, transmission trunks based in transmission lines and complementary compensation “selected” for moderate distances, of the order of 300 to 400 km, with transmission capacity, per trunk, of the order of 1 GW. They do not attain the “critical dimension” economically adequate for energy transmission at very long distance and compatible with the available generation potential for which transmission at very large distance is economically attractive. Otherwise, they did not consider a search of innovative solutions optimized for the applicable power and transmission distance.

We have done studies of non-conventional solutions, deliberately abandoning the criteria of choosing solutions similar to lines and compensation equipment of present systems, but considering very robust criteria of physical validity, ambient impact and joint global optimization of transmission trunk. Such optimization considers, namely: investment and operational costs, including losses, operational flexibility, adequacy for a large range of long-term scenarios and reliability. For instance, very interesting solutions have been obtained, based in alternating current transmission trunks, non-conventional, with unitary transmission capability from 2 GW to 12 GW, without the need of reactive compensation, or with very small reactive compensation, and without the need of intermediate substations. Such trunks can be energized and de-energized switching a single circuit breaker, with moderate switching overvoltages, have moderate losses, very good behavior for load variations and for electromechanical stability of interconnected networks, originate moderate electromagnetic field near the line, have low ambient impact and have cost typically much lower than some recent transmission systems based in conventional solutions (by example, cost ratio of the order of 1 : 5 to 1 : 3).

It was also done a systematic analysis for detection of potentially critical conditions of non-conventional solutions, which may be quite different of critical conditions of conventional systems. Also, were identified procedures to limit eventual undesirable constraints, adequately making use of the specific characteristics of such transmission systems.

In the paper it is presented a discussion of mentioned non-conventional solutions, with emphasis in conceptual aspects and in optimization and validation procedures. Also, as example, it is presented an orientative range of basic parameters of such solutions, in the power and parameters range potentially interesting for transmission electric power from Amazon basin to main consumption regions of Brazil. An example, of a 1000 kV , 2550 km , 8.6 GW transmission trunk, was used for some illustrative examples of the studied non-conventional transmission system. Such examples are representative of requirements for electric transmission in other regions.

An exemplificative cost analysis is also presented, showing that the presented non-conventional transmission systems, for very large distances, have costs much lower (cost ratio less than one to five in example conditions) than solutions based in simple extrapolation of conventional transmission systems. Independently of specific details of the presented example, the reasons of important cost reduction that results of the presented non-conventional solutions are a direct consequence of its basic physical concept, and not a result of specific example conditions.

The paper does not discuss the alternative of DC transmission, whose analysis is not in its scope. So, it also out of its scope a quantitative comparison of costs, and other relevant aspects, of the non-conventional solution presented in this paper with a DC alternative, for very long distance transmission.

As emphasized in this paper, the two solutions (non-conventional AC transmission, discussed in this paper, and DC transmission) have quite different optimization constraints, and their correct comparison imposes a separate optimization of both solution types, and the objective and quantitative comparison of results. In some conditions a hybrid solution may be justified.

However, it must be clarified that some comparisons of AC and DC alternatives presented in some recent documents and papers, result, in our opinion, of non correct analysis of relevant conceptual aspects of AC alternatives adequate for very long distance transmission, namely of the type presented in this paper.

BIBLIOGRAPHY

- [1] National Energy Balance BEN (Brazil), 2005, Base Year 2004, (*in Portuguese*) – Ministry of Mines and Energy (Brazil), 189 p., 2005
- [2] Brazil Electric Energy Atlas, 2d edition (*in Portuguese*) – ANEEL Electric Energy National Agency (Brazil), 243 p., 2005
- [3] Demographic census, 2000 (Brazil) – Brazilian Institute of Geography and Statistics, IBGE, 2004
- [4] Information System of Brazilian Hydroelectric Potential – SIPOT, April 2003, ELETROBRAS
- [5] Decennial Plan of Electric Energy Expansion 2006-2015 (Brazil) (*in Portuguese*) – Ministry of Mines and Energy (Brazil), 378 p., 2006
- [6] C. Portela – Brazilian Electric System – Realities and Options (*in Portuguese*) – Symposium Prof. Carlos Portela 70 years; The Science in Electrical Engineering, 60 p., December 2005

- [7] C. Portela, M. Tavares – Modeling, Simulation and Optimization of Transmission Lines. Applicability and Limitations of Some Used Procedures – *Transmission and Distribution 2002*, IEEE - PES Society, 38 p., Invited speech, <http://www.ieee/pesTD2002>, São Paulo, Brazil, March 2002
- [8] C. Portela, M. Aredes – Very Long Distance Transmission – Proceedings 2003 International Conference on AC Power Delivery at Long and Very Long Distances, pp. 385-394, Novosibirsk, Russia, September 2003
- [9] C. Portela, M. Tavares – A New Methodology to Optimize Large EHV-Transmission System Transient Studies – Proceedings 2003 International Conference on AC Power Delivery at Long and Very Long Distances, pp. 444-454, Novosibirsk, Russia, September 2003
- [10] M. Aredes, E. Emmerik, R. Dias, C. Portela – Facts Applied to Very Long Distance Transmission Lines – Proceedings 2003 International Conference on AC Power Delivery at Long and Very Long Distances, pp. 395-403, Novosibirsk, Russia, September 2003
- [11] M. Aredes, E. Sasso, E. Emmerik, R. Dias, C. Portela – The GTO-Controlled Series Capacitor Applied to Half-Wave Length Transmission Lines – Proceedings International Conference on Power Systems Transients (IPST' 2003), pp. 1-6, New Orleans, United States, September/October 2003
- [12] C. Portela, M. Tavares – Six-Phase Transmission Line . Propagation Characteristics and New Three-Phase Representation – IEEE Transactions on Power Delivery, vol. 8, n° 3, pp. 1470-1483, July 1993
- [13] S. Gomes; N. Martins, C. Portela – Computing Small-Signal Stability Boundaries for Large-Scale Power Systems – IEEE Transactions on Power Systems, vol. 18, n. 2 , pp. 747-752, May 2003
- [14] S. Gomes, S. Varricchio, N. Martins, C. Portela – Modal Analysis of Electromagnetic Transients in ac Networks having Long Transmission Lines – IEEE Transactions on Power Delivery, vol. 20, n° 4, pp. 2623-2630, October 2005
- [15] C. Portela, G. Moreno, M. Tavares – Advantages of Six-Phase Transmission as Compared with Three-Phase Transmission Concerning Environmental Impact – Eighth International Symposium on High Voltage Engineering, ISHVE, Yokohama, Japan, Proceedings, art. 91.04, vol.4, pp. 349-352, August 1993
- [16] C. Portela, M. Tavares, R. Azevedo – A New Line Representation for Transient Studies - Application to a Six-Phase Transmission Line – Eighth International Symposium on High Voltage Engineering, ISHVE, Yokohama, Japan, Proceedings, art. 74.09, vol.4, pp. 245-248, August 1993
- [17] C. Portela – Some Aspects of Very Long Lines Switching – CIGRE SC 13 Colloquium 1995, Florianópolis, art. 2.2, 12 p., September 1995
- [18] C. Portela, S. Gomes – Analysis and Optimization of Non-conventional Transmission Trunks, Considering New Technological Possibilities – VI SEPOPE, Symposium of Specialists in Electric Operational and Expansion Planning, SP-092, pp. 1-6, Salvador, BA, Brazil, May 1998
- [19] E. Watanabe, M. Aredes, C. Portela – Electric Energy and Environment: Some Technological Challenges in Brazil – chapter of book Energy and Environment - Technological Challenges for the Future - editors Y. H. Mori, K. Ohnishi - Springer - ISBN 4-431-70293-8 Springer-Verlag, p. 10-40, 2000
- [20] S. Gomes, C. Portela, N. Martins – Detailed Model of Long Transmission Lines for Modal Analysis of ac Networks – Proceedings International Conference on Power Systems Transients (IPST' 2001), pp. 37-42, Rio de Janeiro, Brazil, June 2001
- [21] C. Portela – Six-Phase Transmission Systems . Functional Characteristics and Potential Application Domains (*in Portuguese*) – X SNPTEE, Curitiba, Brazil, art. CTBA/GSP/27, 8 p., October 1989
- [22] C. Portela, M. Tavares – Behavior and Optimization of a Six-Phase Transmission System for Normal Operation and Transient Phenomena (*in Portuguese*) – XI SNPTEE, Rio de Janeiro, Brazil, art. RJ/GAT/20, 6 p., October 1991
- [23] S. Gomes, C. Portela, C. Fernandes – Principles and Advantages of Using LPNEs and Comparative Results (*in Portuguese*) – XIII SNPTEE, Florianópolis, SC, Brazil, art. FL/GLT/23, 6 p., October 1995
- [24] C. Portela – A Computational System for Optimization of Non-Conventional Transmission Lines (LNC) (*in Portuguese*) – XIV SNPTEE, Belém, Pará, Brazil, 6 p., October 1997
- [25] C. Portela, S. Gomes – Non-Conventional Lines with Large Transmission Capacity - Parametric Analysis (*in Portuguese*) – XV SNPTEE, Foz do Iguaçu, Paraná, Brazil, 6 p., October 1999
- [26] S. Gomes, N. Martins, S. Varricchio, C. Portela - Modal Analysis of Electromagnetic Transients in ac Networks Having Long Transmission Lines – IEEE Transactions on Power Delivery, Volume 20, no. 4, October de 2005, pp. 2623-2630
- [27] C. Portela, J.B. Gertrudes, M. Tavares, J. Pissolato. – Earth Conductivity and Permittivity Data Measurement: Influence in Transmission Line Transient Performance – Electric Power System Research, 76 (2006) 907-915, Elsevier, Volume 76, pp. 907-915

- [28] C. Portela – Present Situation and Perspectives of Brazilian Electric Sector – Perturbations and Risks of Panaceas and Wishes to Control Complex Physical Systems with Rules of Speculative Games (*in Portuguese*)– 58th Annual Meeting of SBPC – Technological Symposium – Power Systems Control – The Electric Energy and the Brazil Development – Florianópolis, SC, Brazil, pp. 1-28, available at www.labspot.ufsc.br, 16 a 21 July 2006
- [29] C. Portela. – Overvoltages and Insulation Coordination (*in Portuguese*), Vols. I, II, III - Vol. I, 349 p. , Vol. II, 304 p. , Vol. III, 140 p. - edition COPPE/UFRJ, Rio de Janeiro, 1982
- [30] Portela, C. – Transient Regimen (*in Portuguese*), Vol. I, II, III, IV - Vol. I, 357 p. , Vol. II, 365 p. , Vol. III, 318 p. , Vol. IV, 280 p. - edition COPPE/UFRJ and ELETROBRÁS, Rio de Janeiro, 1983
- [31] C. Portela – Frequency and Transient Behavior of Grounding Systems, I Physical and Methodological Aspects, II Practical Application Examples - IEEE 1997 International Symposium on Electromagnetic Compatibility, pp. 379-390 - Austin, United States, August 1997
- [32] C. Portela – Soil Electromagnetic Behavior - Ground'98 International Conference on Grounding and Earthing, pp. 53-58 - Belo Horizonte, Brazil, April 1998
- [33] C. Portela – Statistical Distribution of Parameters of Lightning Impulses in Antennas, Towers and Buildings - Methodological Aspects - Practical Application Examples - IEEE 1998 International Symposium on Electromagnetic Compatibility, pp. 1018-1023, pp. 259-264 - Denver, United States, August 1998
- [34] C. Portela – Measurement and Modeling of Soil Electromagnetic Behavior - IEEE 1999 International Symposium on Electromagnetic Compatibility, pp. 1004-1009, Seattle, United States, August 1999
- [35] C. Portela – Statistical Aspects of Soil Electromagnetic Behavior in Frequency Domain - Ground'2000 International Conference on Grounding and Earthing, Proceedings, pp. 99-104 - Belo Horizonte, Brazil, June 2000
- [36] C. Portela – Grounding Requirements to Assure People and Equipment Safety Against Lightning - IEEE 2000 International Symposium on Electromagnetic Compatibility, pp. 969-974, Washington, DC, United States, August 2000
- [37] C. Portela – Influence in Lightning Effects of Soil Electromagnetic Behavior in Frequency Domain - Proceedings International Conference on Lightning Protection 2002, ICLP 2002, vol. I, pp. 394-399 - Cracow, Poland, September 2002
- [38] C. Portela – Temperature Increase of Grounding Conductors due to Lightning - Proceedings International Conference on Lightning Protection 2002, ICLP 2002, vol. I, pp. 321-326 - Cracow, Poland, September 2002
- [39] C. Portela, M. G. Alvim, A. R. Nobrega – The Importance of Reliable Measurements of Lightning Currents to Electric Power Companies – 2006 19th International Lightning Detection Conference and 1st International Meteorology Conference, Tucson, Arizona, United States, April 2006
- [40] C. Portela, M. G. Alvim – Lightning Physics, Measurement And Consequences – Modeling Limitations and Requirements in Engineering Applications, GROUND'2006 and 2nd LPE - International Conference on Grounding and Earthing & 2nd International Conference on Lightning Physics and Effects, Proceedings, p. 109-115, Maceió, Brazil, November, 2006
- [41] C. Portela, M. G. Alvim – Lightning Physics, Measurement And Consequences – Examples of Modeling Limitations and Requirements in Engineering Applications, GROUND'2006 and 2nd LPE - International Conference on Grounding and Earthing & 2nd International Conference on Lightning Physics and Effects, Proceedings, p. 117-122, Maceió, Brazil, November, 2006
- [42] J. Clavio, C. Portela – A Methodology for Electromagnetic Transients Calculation – An Application for the Calculation of Lightning Propagation in Transmission Lines – IEEE Transactions on Power Delivery, vol. 22, n^o. 1, pp. 492-536, January 2007
- [43] A. Lima, C. Portela – Inclusion of Frequency Dependent Soil Parameters in Transmission Line Modeling – IEEE Transactions on Power Delivery, vol.22, n^o. 1, pp. 492-499, January 2007
- [44] J. Stratton – Electromagnetic Theory – McGraw-Hill, 1941
- [45] K. Berger, R. B. Anderson - Parameters of Lightning Flashes - Electra n^o 41, pp. 23-37, July 1975
- [46] R. H. Golde – Lightning - Vol. 1. - London, 1977.
- [47] R. Guimarães, J. Fernandes, J. Silva, J. Oliveira, L. Menezes, A. Saliba, R. Amaro, M. Takai, P. Borges – Compact Structure of Cross-Rope Type for 500 kV Transmission Line (*in Portuguese*) – XVI SNPTTE, Campinas, São Paulo, Brazil, 6 p., October 2001

ACKNOWLEDGEMENT

The author Carlos Portela thanks the support received from *CNPq National Council of Scientific and Technological Development (Brazil)* in part of research work in which this paper is based.

ANNEX 1 – Example of a LNC line of 800 kV, $P_c = 4.8$ GW, 2550 km

In order to show the flexibility of adjusting the basic parameters of LNC lines, and a comparison with the example of the 1000 kV line, in this Annex, namely in Figs. A1-1, A1-2 and A1-3, we present a few results of other example: a 800 kV, 2550 km, three-phase LNC line, with characteristic power $P_c = 4.8$ GW, without reactive compensation, switched from one extremity (all the line). Sustained overvoltage in one terminal (opened) is 1.015 pu (referred to the other terminal voltage). Its behavior is similar to the 1000 kV line example (in relation to the applicable characteristic power).

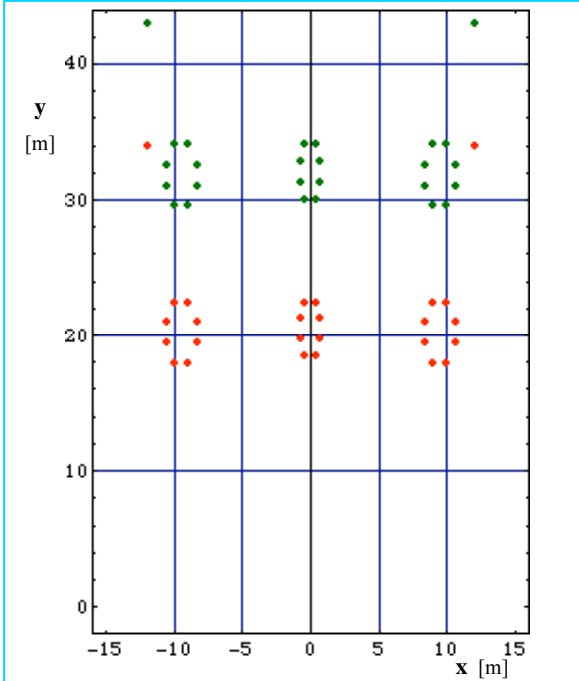


Fig. A1-1 – Position of phase cables (eight cables per phase bundle) and ground wires, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, without wind. Position at mid-span is represented in red, and, near the structures, in green. Coordinate x is the algebraic horizontal distance to line's vertical symmetry plane. Coordinate y is distance to soil (assuming flat soil).

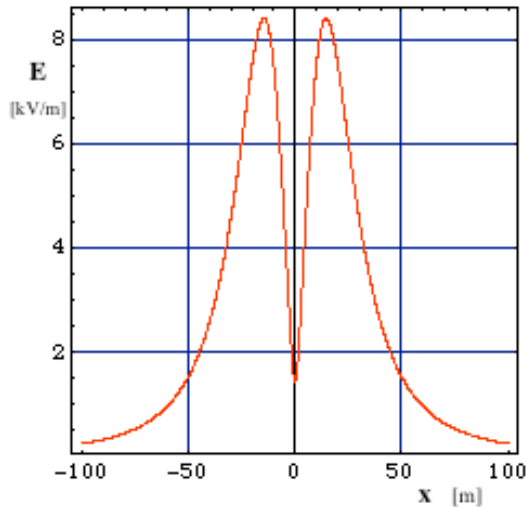


Fig. A1-2 – Electric field, at ground level, at mid-span, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, without wind.

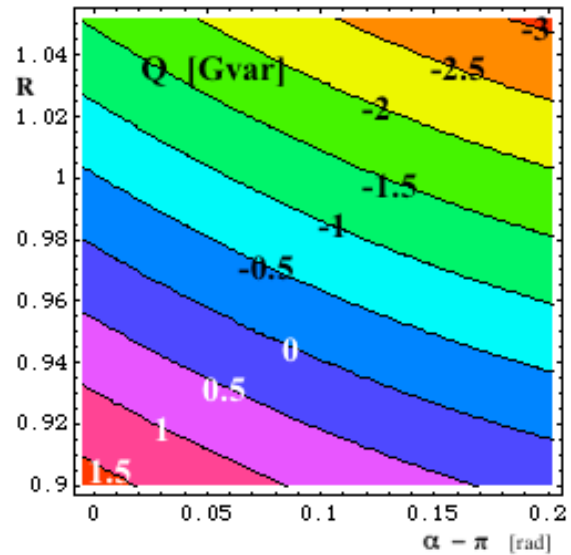
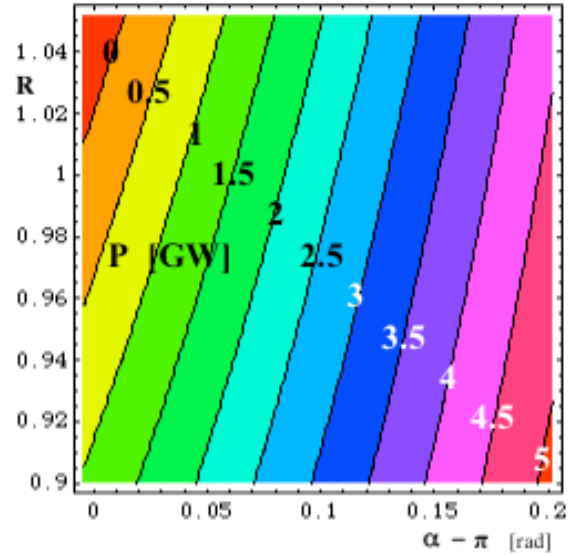


Fig. A1-3 – Power, P (in GW), and reactive power, Q (in Gvar), at line terminal 1, with voltage $U_1 = 800$ kV, in function of phase difference, α , and ratio, R , between modules of voltages at terminals 2 and 1.

For this example, we represent, schematically, in Figs. A1-4 to A1-6, three examples of structures, namely: a guyed structure similar to the example structure shown for the example of a 1000 kV line (Figs. 12 to 14); one classical “chainette” type structure; one structure of the type “cross-rope” (CCRS – compact cross-rope suspension), that is a simplified version of the “chainette” type.

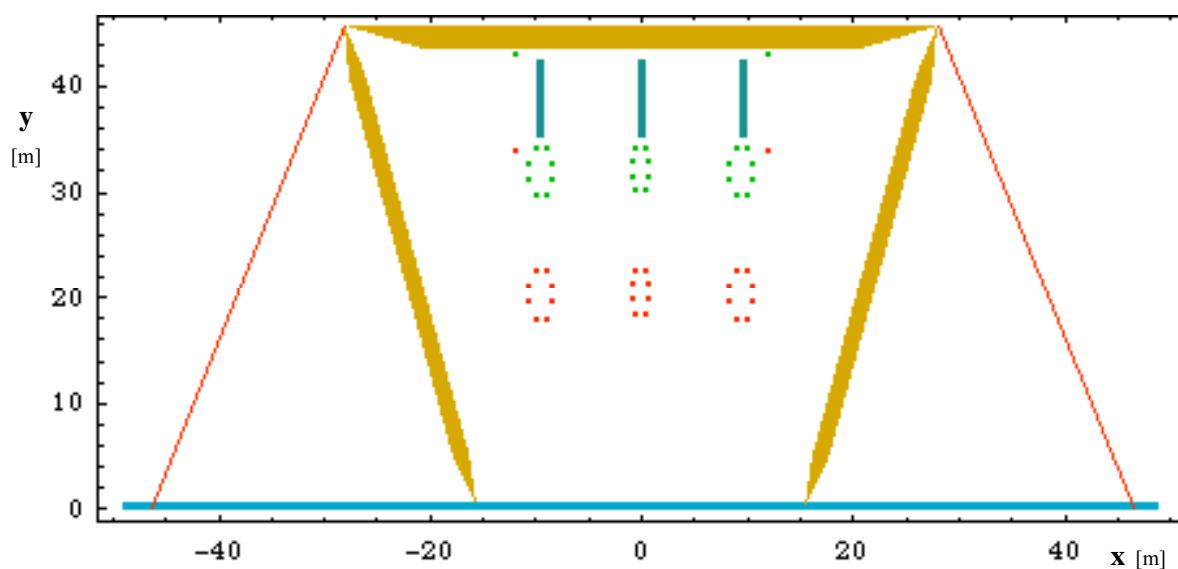


Fig. A1-4 – Guyed structure alternative, for example line, and position of phase cables (eight cables per phase bundle) and ground wires, in the example line, for cables at 25 °C, in a 500 m span, in flat soil, without wind.

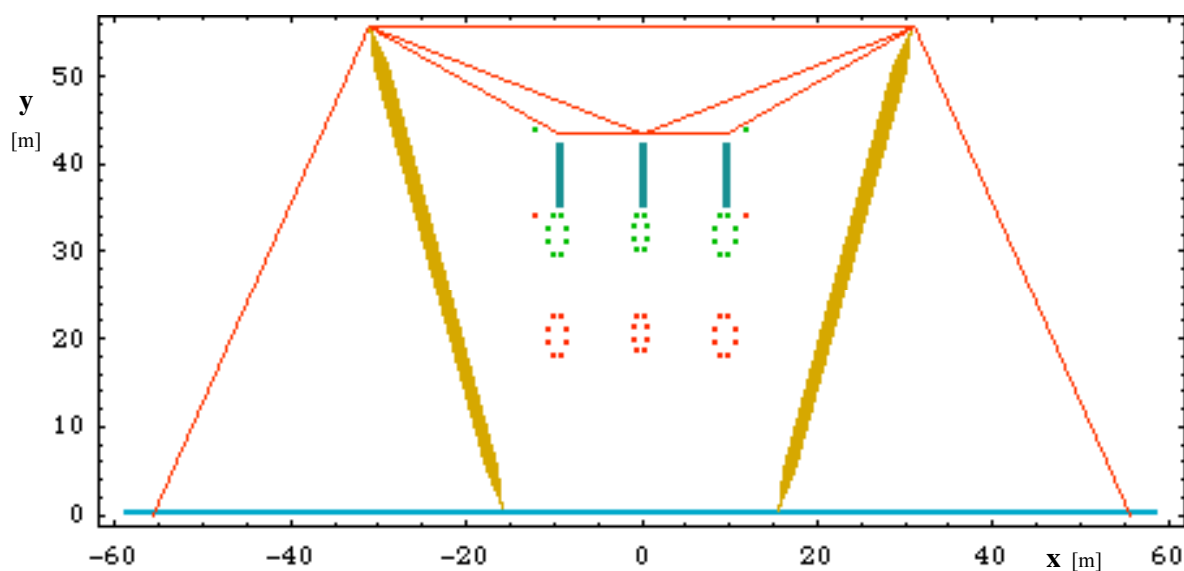


Fig. A1-5 – Chainette type structure.

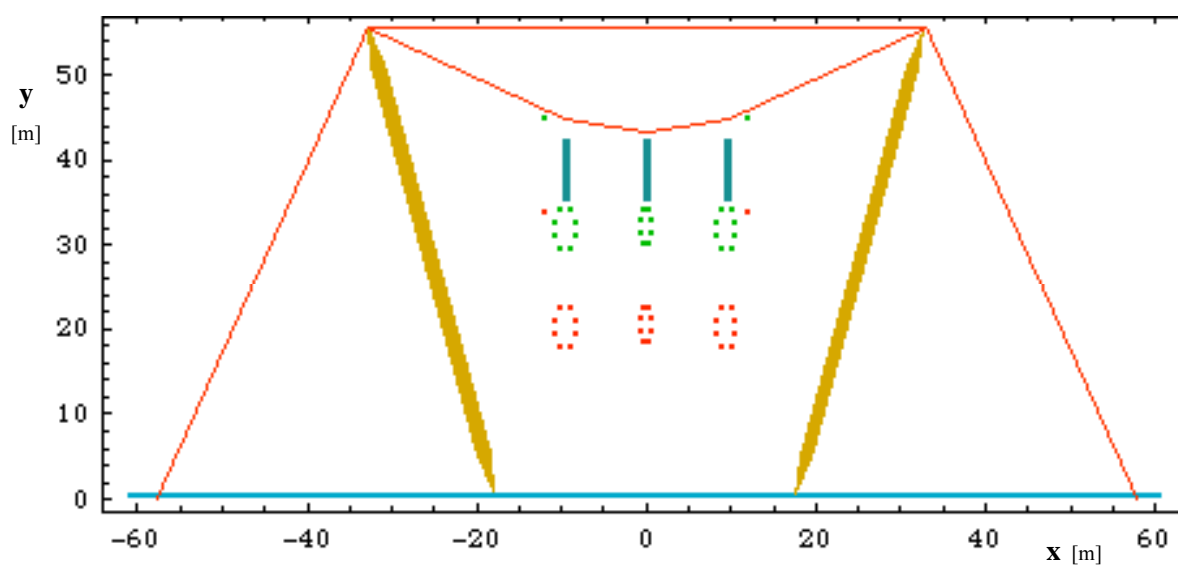


Fig.A1-6 – Cross-rope type structure.

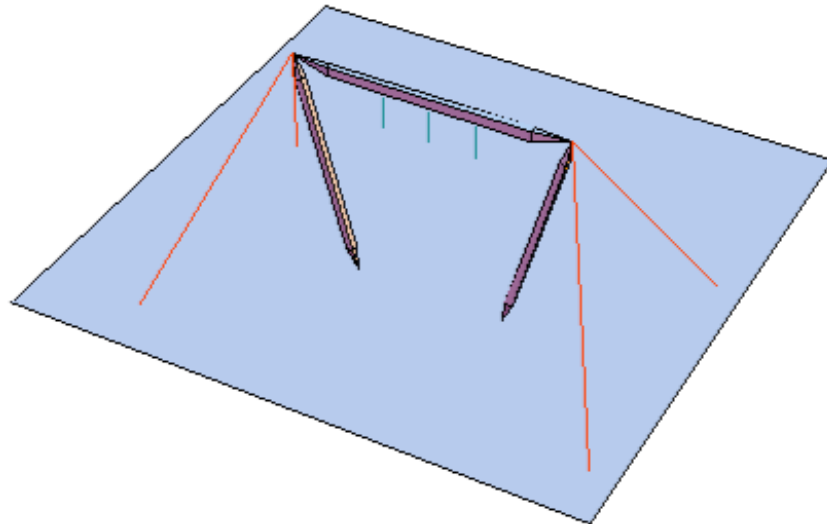


Fig. A1-7 – Three-dimensional representation of the structure of Fig. A1-4 (“guyed”).

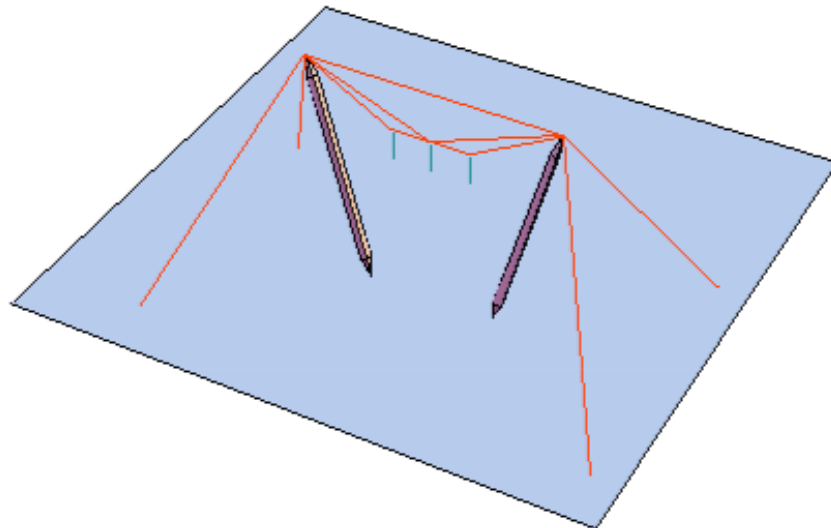


Fig. A1-8 – Three-dimensional representation of the structure of Fig. A1-5 (“chainette”).

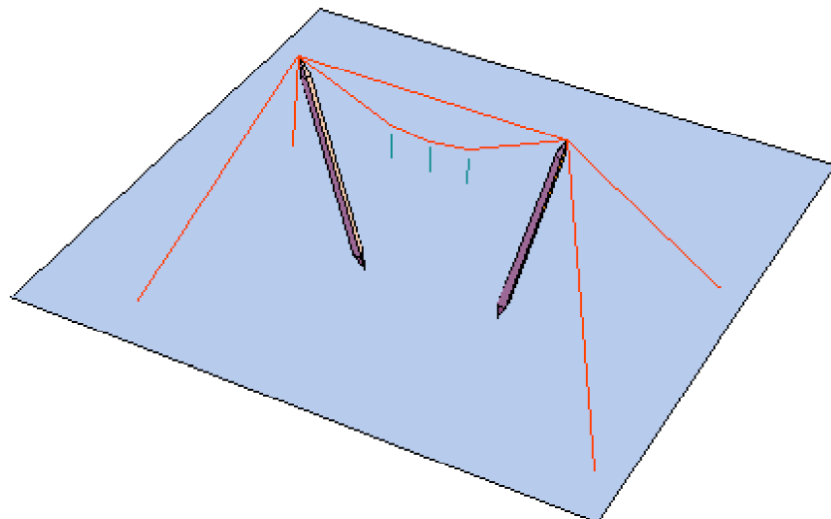


Fig. A1-9 – Three-dimensional representation of the structure of Fig. A1-6 (“cross-rope”).

The three structure types, and other types, not represented here, are potentially interesting and deserve consideration for a significant spectrum of specific project conditions. Naturally, each structure type has its specific characteristics that must be duly taken into account. For instance, in “cross-rope” type, the connection “points” of insulator chains to structure cables have significant horizontal and vertical

displacement for strong winds, different for the three phase bundles. Such behavior may originate specific vibration modes, and care must be taken, e.g. in what concerns dampers and bundle spacers, avoiding material excessive mechanical ageing due to low damped resonance frequencies; in the Brazilian experience with “cross-rope” structures several precautions were taken, with good operational experience, as commented below.

Important aspects for comparison of structure types, in Brazil, are the wind applicable conditions and criteria, and constraints for consequences of possible anomalous occurrences, e.g. wind more severe than project assumptions, broken insulator chain, broken phase bundle, structure crash. In other countries, other anomalous conditions may be also important, e.g. unforeseen low temperatures, unforeseen ice accumulation, earthquakes, vandalism, terrorism.

Due to the several “effects” that are considered in project criteria, and in order to identify clearly the severity of wind conditions in what concerns projects comparison, we have chosen, as representative parameter of assumed wind criteria, the maximum equivalent wind speed, V , incident in cables, in steady state (incorporating the resultant effects of “nominal wind speed”, spatial and time wind distribution, influence of distance to ground, wind velocity exposure, gust response factor). For several important line projects in Brazil (including part of the lines with “cross-rope” type structures), it has been assumed, for adequate electrical “line operation”, and according applicable conditions of insulation chains and of complementary elements, V of the order of 110 km/h. The three examples of structure type represented in Figs. A1-4 to A1-9 follow these criteria.

We now present a short comment related to Brazilian experience with “cross-rope” type structure, that was introduced in the Amazon region about five years ago, for 500 kV lines [47], having good performance so far. About 3000 km of lines using “cross-rope” structures have already been constructed in Brazil. According criteria used in several projects, in some parts of Amazon region wind has been assumed lower than frequently adopted for other regions of Brazil.

Anyhow, the choice of structure type and applicable criteria must be done carefully according the specific conditions and with careful judgment of available information.

We indicate schematically, in Fig. A1-10, a possible variant of “cross-rope” structure for the example of a LNC line of 800 kV, $P_c = 4.8$ GW, 2550 km, presented in this Annex 1. The example of Fig. A1-10 considers conditions similar to what has been assumed in some 500 kV transmission lines’ projects for the Amazon region, with “cross-rope” structures. Namely, it has been assumed, for adequate electrical “line operation”, V of the order of 90 km/h. For mechanical effects, the geometry of Fig. A1-10 is adequate for eventual higher wind speed. The choice of structural steel material and detailed dimensions of cables and masts’ elements must be chosen according applicable constraints. Also some flexibility exists in what concerns electrical “line operation”, with some changes in geometry and in structural elements.

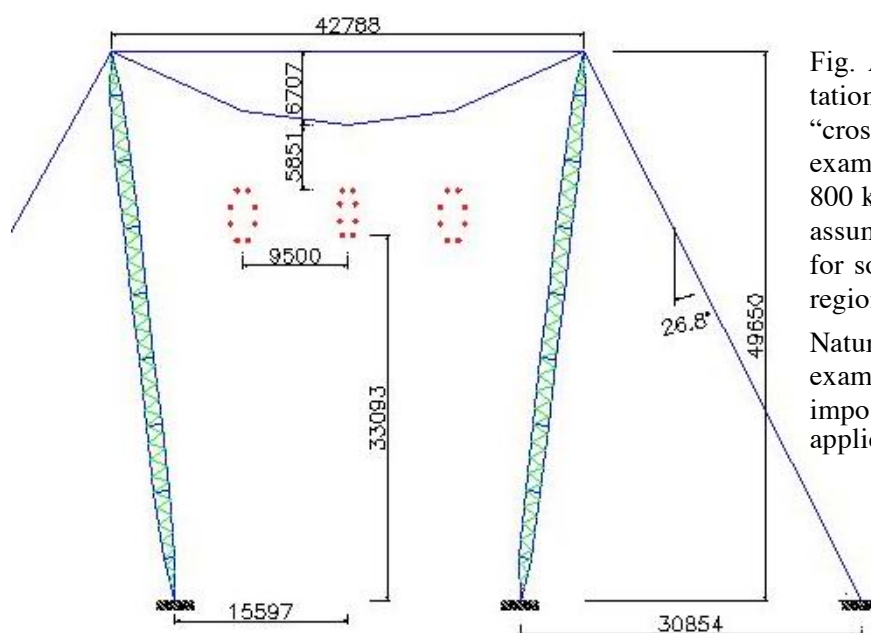


Fig. A1-10 – Schematic representation of a possible variant of “cross-rope” type structures for the example of a 800 kV LNC line of 800 kV, $P_c = 4.8$ GW, considering assumptions similar to those used for some 500 kV lines in Amazon region.

Naturally, this variant is only an example. Any structure choice imposes a careful analysis of applicable conditions.