Very Long Distance Transmission

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Abstract - **The problem of AC transmission at very long distance was studied using several methods to consider some transmission system alternatives, interpreting the dominant physical and technical phenomena, and using simulations to detail and confirm general analysis.**

The results obtained were quite interesting. Namely, they have shown that: electric transmission at very long distance is quite different of what would be expected by simple extrapolation of medium distance transmission experience; to optimize a very long distance transmission trunk, a more fundamental and open approach is needed.

The paper discusses the following topics: *i)*. essential aspects of very long distance transmission; *ii)*. basic physical aspects of very long lines operating conditions; *iii)*. basic physical aspects of very long lines switching; *iv)*. transmission line optimization; *v)*. importance of joint optimization of line, network and operational criteria.

Index Terms - AC transmission, optimization, very long distance.

I. Essential Aspects of Very Long Distance Transmission

The problem of AC transmission at very long distance was studied using several methods to consider some transmission system alternatives, interpreting the dominant physical and technical phenomena, and using simulations to detail and confirm general analysis [1-23].

The results obtained were quite interesting. Namely, they have shown that: electric transmission at very long distance is quite different of what would be expected by simple extrapolation of medium distance transmission experience; to optimize a very long distance transmission trunk, a more fundamental and open approach is needed. For example:

- Very long distance lines do not need, basically, reactive compensation, and, so, the cost of AC transmission systems, per unit length, e.g., for 2800 km, is much lower than, e.g., for 400 km.
- The choice of non-conventional line conception is appropriate for very long transmission systems, including eventually:
  - "Reduced" insulation distances, duly coordinated with adequate means to reduce switching overvoltages;
  - Non-conventional geometry of conductor bundles, six-phase lines, surge arresters distributed along the line.
- Switching transients, for several normal switching conditions, are moderate, in what concerns circuit breaker duties and network transients' severity, for lines and equipment. Namely, line energizing, in a single step switching, of a 2800 km line, without reactive compensation, originates overvoltages that are lower than, or similar to, overvoltages of a 300 km line with reactive compensation.
- There are some potentially severe conditions quite different from typical severe conditions in medium distance systems, e.g., in what concerns secondary arc currents, and requirements to allow fault elimination without the need of opening all line phases. The severity of such conditions is strongly dependent of circuit breaker and network behavior. Due to peculiar characteristics of long lines' transients, it is possible to reduce drastically the severity, with fast switching and appropriate protection schemes.
- Quite good results can be obtained with a careful coordination of circuit breakers with line and network, namely with synchronized switching, coordination of several circuit breakers and closing auxiliary resistors. Eventually, special schemes can be used to limit overvoltages for some quite unfavorable conditions of fault type and location.

Due to the lack of practical experience of very long transmission lines, and the fact that they have characteristics quite different of traditional power transmission lines and networks, a very careful and systematic analysis must be done, in order to obtain an optimized solution.

II. Basic Physical Aspects of Very Long Lines Operating Conditions

In order to clarify the most important aspects of very long lines' characteristics, let us assume a line with no losses, total length $\mathbf{L}$, longitudinal reactance per unit length $\mathbf{X}$, transversal admittance per unit length $\mathbf{Y}$, both for non-homopolar conditions, at power frequency, $\mathbf{f}$. In case of longitudinal compensation, and or transversal compensation, at not very long distances along the line, such compensation may be "included" in "equivalent average" $\mathbf{X}$ and $\mathbf{Y}$ values. The electric length of the line, Θ , at frequency $\mathbf{f}$ (being $\omega = 2\,\pi\,\mathbf{f}$ and $\mathbf{v}$ the phase velocity), is [9]:

$$\Theta = \sqrt{\mathbf{X}\,\mathbf{Y}}\;\mathbf{L} = \frac{\omega}{\mathbf{v}}\;\mathbf{L} \qquad\qquad \mathbf{v} = \frac{\omega}{\sqrt{\mathbf{X}\,\mathbf{Y}}} \tag{1}$$

If $\mathbf{X}$ and $\mathbf{Y}$ values do not include compensation, the phase velocity, $\mathbf{v}$, is almost independent of line constructive parameters, and of the order of 0.96 to 0.99 times the electromagnetic propagation speed in vacuum.

The characteristic impedance, $\mathbf{Z}_c$, and, at a reference voltage, $\mathbf{U}_0$, the characteristic power, $\mathbf{P}_c$, are:

$$\mathbf{Z}_c = \sqrt{\frac{\mathbf{X}}{\mathbf{Y}}} \qquad\qquad \mathbf{P}_c = \frac{\mathbf{U}_0^{\,2}}{\mathbf{Z}_c} \tag{2}$$

Let us consider eventual longitudinal (series) and transversal (shunt) reactive compensation, along the line, at distances not too long (much smaller than a quart wave length at power frequency), by means of "reactive compensation factors", ξ, η. Being $\mathbf{X}_0$, $\mathbf{Y}_0$ the, per unit length, longitudinal reactance and transversal admittance, of the line, not including compensation, and $\mathbf{X}$, $\mathbf{Y}$ the "average" per unit length corresponding values, including compensation, we have:

$$\mathbf{X} = \xi\;\mathbf{X}_0 \qquad\qquad \mathbf{Y} = \eta\;\mathbf{Y}_0 \tag{3}$$

Without reactive compensation, $\xi = 1$, $\eta = 1$. For example, in a line with 30 % longitudinal capacitive compensation and 60 % transversal inductive compensation, we have $\xi = 0.70$, $\eta = 0.40$. Without reactive compensation, $\xi = 1$, $\eta = 1$.

The eventual longitudinal and transversal reactive compensation has the following effect:

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$$\Theta = \sqrt{\xi\eta}\ \Theta_0 \qquad \mathbf{Z}_c = \sqrt{\frac{\xi}{\eta}}\ \mathbf{Z}_{c0} \qquad \mathbf{P}_c = \sqrt{\frac{\eta}{\xi}}\ \mathbf{P}_{c0} \qquad (4)$$

The index $_0$ identifies corresponding values without reactive compensation ($\xi = 1$, $\eta = 1$). For example, in a line with 600 km , at 60 Hz ($\Theta_0 = 0.762$ rad), using capacitive 40% longitudinal compensation ($\xi = 0.60$) and inductive 65% transversal compensation ($\eta = 0.35$), Θ is reduced to 0.349 rad (equivalent to 275 km at 60 Hz), characteristic impedance is multiplied by 1.31 and characteristic power by 0.76.

In traditional networks, with line lengths a few hundred kilometers, the reactive compensation is used to reduce Θ to "much less" than $\pi/2$ (a quart wave length) and to adapt $\mathbf{P}_c$, which, together with Θ, defines voltage profiles, some switching overvoltages and reactive power absorbed by the line.

In case of very long distances (2000 to 3000 km), to reduce Θ to much less than $\pi/2$ would imply in extremely high levels of reactive compensation, increasing the cost of transmission (doubling, according some published studies of "optimized" transmission systems), and with several technical severe consequences, due to a multitude of resonance type conditions. The solution we have found [1-10], and discuss above, for very long distances, is to work with Θ a little higher than π , so avoiding the need of high levels of reactive compensation, and obtaining a transmission system much cheaper and with much better behavior.

Neglecting losses, the behavior of the line, at power frequency, in balanced conditions, is defined by Θ and $\mathbf{Z}_c$.

Let us assume that voltages at both extremities, $\mathbf{U}_1$, $\mathbf{U}_2$, in complex notation, are:

$$\mathbf{U}_2 = \mathbf{U}_0 \qquad\qquad \mathbf{U}_1 = \mathbf{U}_0\ e^{i\,\alpha} \qquad (5)$$

Besides a proportionality factor $\mathbf{P}_c$, the active and reactive power, at both extremities and along the line, depend on Θ and α. Let us consider lines with the following electric lengths:

a) $\Theta = 0.05\ \pi$ (about 124 km at 60 Hz)
b) $\Theta = 0.10\ \pi$ (about 248 km at 60 Hz)
c) $\Theta = 0.90\ \pi$ (about 2228 km at 60 Hz)
d) $\Theta = 0.95\ \pi$ (about 2351 km at 60 Hz)
e) $\Theta = 1.05\ \pi$ (about 2599 km at 60 Hz)
f) $\Theta = 1.10\ \pi$ (about 2722 km at 60 Hz)

For these six examples, Fig. 1 shows, in function of α :

- The transmitted active power, $\mathbf{P}$.
- The reactive power, $\mathbf{Q}$, absorbed by the line (sum of reactive power supplied to the line at both terminals).
- The transversal voltage (modulus), $\mathbf{U}_m$, at line midpoint.

Examples **a)**, **b)** correspond to "usual" lengths of relatively short lines. They must be operated in vicinity of $\alpha = 0$, in which an α increment increases the transmitted power. Transmitted power may exceed the characteristic power, with an increase of the reactive power absorbed by the line.

Examples **c)**, **d)**, **e)**, **f)** correspond to very long lines. In examples **c)**, **d)**, the lengths are little shorter than half wavelength ($\Theta = \pi$) and, in examples **e)** , **f)** , they are a little higher than half wave length. Note the line lengths in examples **c)** , **d)** , **e)** , **f)** are longer than a quart wavelength ($\Theta = \pi/2$). For these examples **c)**, **d)**, **e)**, **f)**, in vicinity of $\alpha = 0$, the voltage at line's central region and the reactive power consumption are extremely high, compared, respectively, with voltage at line extremities and transmitted power.

For examples **c)**, **d)**, in vicinity of $\alpha = \pi$, the derivative of transmitted power in relation to α is negative, and, so, the natural stabilizing effect of a positive derivative does not occur. This effect is one of the reasons why traditional alternating current electrical networks are basically stable (with few exceptions), considering electromechanical behavior of generating groups and loads. Unless extremely complex control systems are considered, affecting all main network power stations, it is not adequate to have transmission trunks with length between a quarter and a half wave length ($\pi/2 \le \theta \le \pi$) and operating in the vicinity of $\alpha = \pi$.

For examples **e)**, **f)** In vicinity of $\alpha = \pi$, the derivative of transmitted power in relation to α is positive, and, so, the natural stabilizing effect of a positive derivative occurs, similarly with the behavior of short lines near $\alpha = 0$. Moreover, in the vicinity of $\alpha = \pi$, the behavior of the line, seen from line terminals, is similar to the behavior of a short line, in the vicinity of $\alpha = 0$, for transmitted power in the range $-\mathbf{P}_c \le \mathbf{P} \le \mathbf{P}_c$. The reactive power consumption of the line is moderate, and the voltage along the line does not exceed $\mathbf{U}_0$. The main different aspect is related to the voltage at middle of the line, which is proportional to transmitted power. If characteristic power is referred to maximum voltage along the line, the maximum transmitted power is limited to the characteristic power (what does not occur in short lines).

At least for a point to point long distance transmission, the fact that voltage at the middle of the line varies, between 0 and $\mathbf{U}_0$, does not imply major inconvenience. If, for a mainly point to point long distance transmission, it is wished to connect some relatively small loads, in the middle part of the line, there are several ways to do so. It is convenient to adopt some non-conventional solution, adapted to the fact that, in central part of the line, the voltage is not "almost constant", but varies according to the transmitted power, and besides, the current is "almost constant". It is an easy task for FACTS technologies, and some useful ideas can be obtained with ancient transmission and distribution systems of "constant current".

Lines with an electric length almost equal to half wave length ($\Theta = \pi$), do not behave in convenient way. They are near a singular point, with sign changes of derivatives of some magnitudes in relation to others, what originates several important troubles, namely related to control instabilities and eventual physical basic instability. Fig. 2 shows an amplification of Fig. 1 , for examples **e)** and **f)** , in the range of "normal operating conditions", with maximum voltage along the line limited to $\mathbf{U}_0$.

As shown with previous simplified discussion, for long distance transmission, there are several important reasons to choose an electric length of the line, Θ , a little higher than half of the wave length, in what concerns normal operating conditions and inherent investment. The "exact" choice is not critical. A range $1.05\ \pi \le \Theta \le 1.10\ \pi$ is a reasonable first approach. Also for "slow" and "fast" transient behavior, this choice has very important advantages, as discussed below.

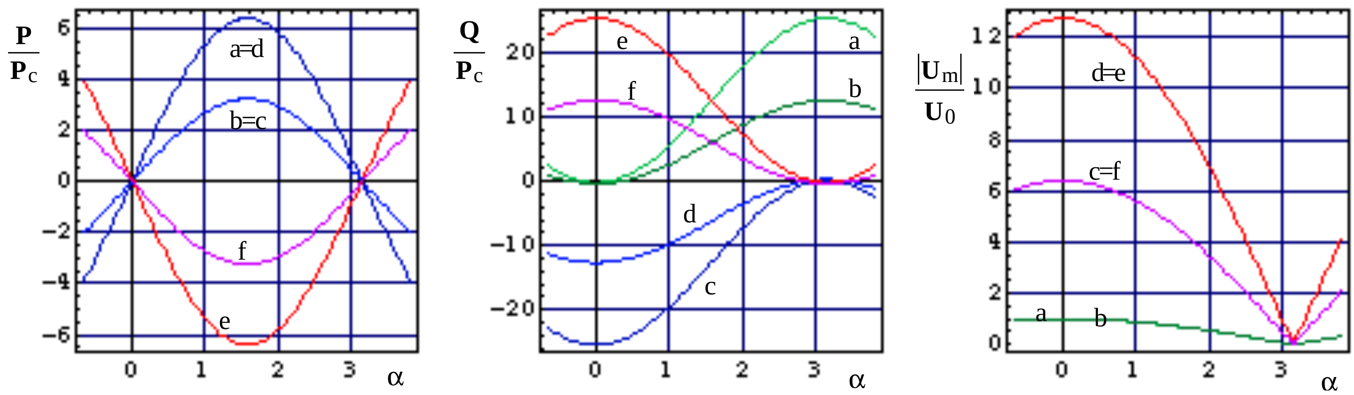


Fig. 1 - Transmitted power, $\mathbf{P}$, reactive power absorbed by the line, $\mathbf{Q}$, modulus of voltage at middle of the line, $|\mathbf{U}_m|$, in function of α, for six examples.

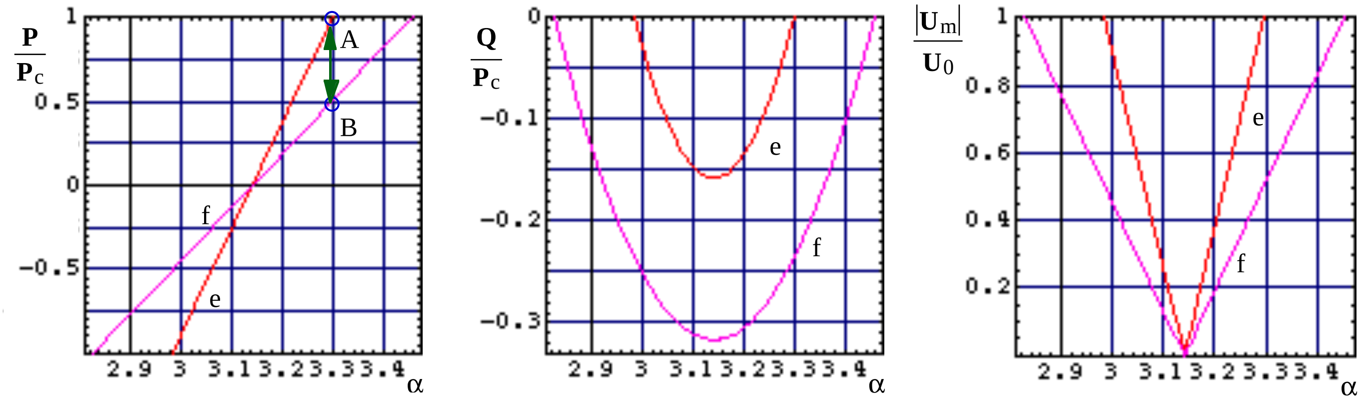


Fig. 2 - Transmitted power, $\mathbf{P}$, reactive power absorbed by the line, $\mathbf{Q}$, modulus of voltage at middle of the line, $|\mathbf{U}_m|$, in function of α , for two examples of very long lines, in normal operating range.

The solution of long distance transmission with Θ a little higher than π (e.g. $1.05\ \pi \leq \Theta \leq 1.10\ \pi$) is quite robust for electromechanical behavior and also for relatively slow transients, associated with voltage control.

For instance, a relatively small reactive control, equivalent to a change in Θ , allows a fast change in transmitted power, in times much shorter than those needed to change the mechanical phase of generators, as represented schematically in Fig. 2 by an arrow and "points" **A** , **B**. Let us assume the line of example **e)** , transmitting a power $\mathbf{P} = \mathbf{P}_c$ (operating point **A** of Fig. 2). A FACTS reactive control that changes Θ from 1.05 to 1.10, what can be done very rapidly, passing the operating point to **B**, changes the transmitted power from 1.0 $\mathbf{P}_c$ to 0.5 $\mathbf{P}_c$, maintaining the phase difference between line terminals. A FACTS system, with control oriented for its effect on Θ , can be very efficient for electromechanical stability.

It must be mentioned that, for balanced conditions, reactive compensation does not need capacitors or reactors to "accumulate energy". In balanced conditions, for three or six phase lines, the instantaneous value of power transmitted by the line (in "all phases") is constant in time, and does not depend on reactive power (what is different of the case of a single phase circuit), and, so, reactive power behavior can be treated by instantaneous transfer among phases, e.g. by electronic switching, with no basic need of capacitors or reactors for energy accumulation (differently of what would be the case of a single phase line).

III. Basic Physical Aspects of Very Long Lines Switching

In order to allow a quite simple interpretation of the effect of line length on line switching overvoltages, it is convenient to consider a very simple line model [17], that allows to take into account the dominant physical effects, with a minimum number of parameters, and that, for most important effects, can be treated by very simple analytical procedures, directly in phase domain. The main characteristics of long line switching are explained with such model, as it has been confirmed with extensive detailed simulation methods.

Let us consider the switching on of a three or six-phase line from an infinite bus-bar, with sinusoidal voltage of frequency f and amplitude $\hat{U}$, with simultaneous switching on of all phases, and neglecting losses' effects in propagation. We have shown [17] that the maximum switching overvoltage (for most unfavorable switching instant), in successive time intervals $[(2\,n - 1)\ T < t < (2\,n + 1)\ T$, being T the "propagation time" along the line], associated to increasing number, n , of wave reflections, is:

$$\mathrm{Max}_n[u_{2k}(t)] = \mathbf{S}^{*n}_{max}\,\hat{U} \qquad \mathbf{S}^{*n}_{max} = 2\,|\mathbf{S}_n| = 2\left|\frac{1-\mathbf{r}^n}{1-\mathbf{r}}\right| \qquad (6)$$

The global maximum of $u_{2k}(t)$, $\mathrm{Max}[u_{2k}(t)]$, is the envelope of relative maxima, for all n values. Such envelope is:

$$\mathrm{Max}[u_{2k}(t)] = \mathbf{S}^{*}_{max}\,\hat{U} \qquad \mathbf{S}^{*}_{max} = \frac{4}{|1-\mathbf{r}|} = \frac{4}{|1+e^{-i2\theta}|} \tag{7}$$

$$\mathbf{S}^{*}_{max} = 2\sec\theta \tag{8}$$

being

$$\mathbf{r} = -\,e^{-i2\theta} \qquad \theta = \omega T \tag{9}$$

θ "electric length" of the line (in radians) at power frequency

In Fig. 3 we represent the coefficients $\mathbf{S}^{*n}_{max}$ and $\mathbf{S}^{*}_{max}$, in function of line electric length, θ . This global maximum is the double of voltage at no load end, in stabilized conditions, at power frequency (whose value is $\hat{U}_0 = \sec\theta\,\hat{U}$). So, in assumed conditions, the ratio of maximum overvoltage, at open line end, and source peak voltage, is function, only, of "electric line length", θ , at power frequency.

Let us consider two examples, Example 1 with $\theta = 1.0$, Example 2 with $\theta = 3.5$ (line lengths of about 788 km and 2760 km , at 60 Hz). Corresponding $\mathbf{S}^{*}_{max}$ values are, respectively, 3.70 and 2.14 . In Fig. 4 we represent, for these two examples, the open line terminal phase to ground voltage (taking source peak phase to ground voltage as unity), considering infinite source and simultaneous closing of all phases. In each graphic are represented two curves. For one curve, the closure, of represented phase, occurs when source voltage is zero, and, for the other, when such source voltage is maximum. The abscissa scales are graduated in $\tau = \omega t$. Maximum overvoltages, found only with these two switching instants, are practically equal to values given by $\mathbf{S}^{*}_{max}$ formula.

For illustrative purposes, we represent, in Fig. 5, for examples 1 and 2, the voltage in the third phase to close, assuming a delay of 2 ms between the second and the first phase closures, and a delay of 2 ms between the second and the third. In Fig. 6, we represent, for examples 1 and 2, the voltages to ground in the three phases of open end line terminal, for synchronized switching on. Comparison of this curves with those of Fig. 5 and 6, illustrates the order of magnitude of switching overvoltage reduction that results of synchronized switching on.

The curves of Fig 3, in the range of $\theta \le \pi/2$, express the well known fact that line switching on has an increasing severity with the line length. This fact is the reason of traditional use of shunt reactors and or series capacitors in lines with a few hundred kilometers, in order to reduce the equivalent electric "length", θ , of the line, and, so, to reduce switching overvoltages. The range $\theta \ge \pi/2$ of those curves express, in a similar way, the main severity aspects of line switching on, for very long lines.

Electric line lengths between $\pi/2$ and π must be avoided, in principle, due to power frequency and power control aspects. Electric line length very close to π must also be avoided, due to the fact that it is a "singular" condition, namely for power control of electric network. For electric line lengths a little higher than π (e.g. $3.2 < \theta < 3.5$), however, lines have quite interesting properties. Namely, switching overvoltages are quite moderate, and similar to those of relatively short lines.

So, for transmission at distances of the order of 2 500 to 3 000 km, as is the case for transmission from Amazonian Region to Southeast Region, in Brazil, the natural way, for AC transmission, is to have transmission trunks with no basic reactive compensation, instead of extrapolating the traditional practice of line strong reactive compensation of long lines. In several aspects, the behavior of an uncompensated line is much better than the behavior of a strongly reactive compensated line, and the cost of an uncompensated line is much lower.

The main objective of the previous analysis is to identify and explain the dominant physical aspects of line switching on, and the influence of line length, for very long lines. It shows why it is not applicable the direct and simple extrapolation of common practices for relatively short lines. It also shows that and why direct switching on, in a single step, of a very long line, with no reactive compensation, originates moderate overvoltages, much lower than overvoltages obtained in switching on lines with a few hundred kilometers length.

A similar analysis explains, also, the several other aspects of very long lines behavior, for different transient phenomena, including those associated to various types of faults and secondary arc aspects for single phase faults.

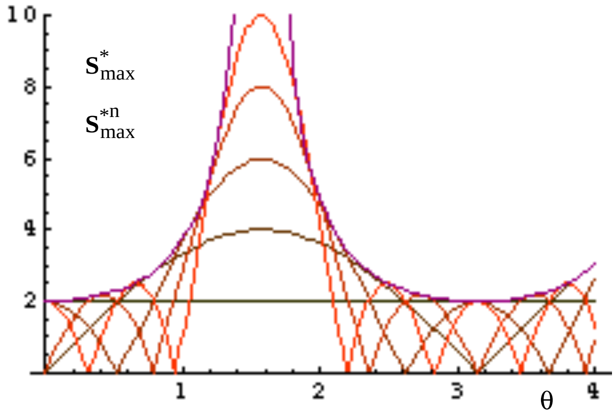
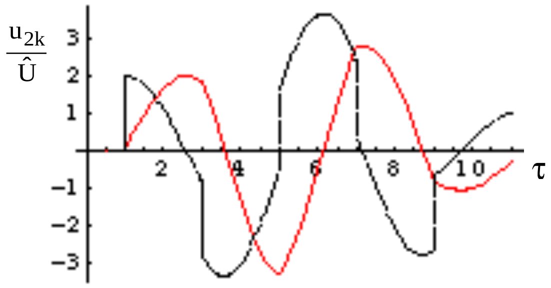
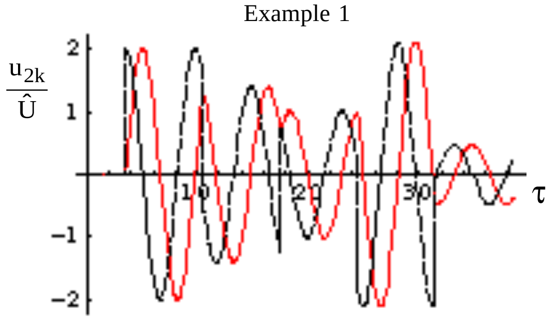


Fig. 3 - Coefficients $\mathbf{S}^{*n}_{max}$ and $\mathbf{S}^{*}_{max}$, in function of the line electric length, θ .

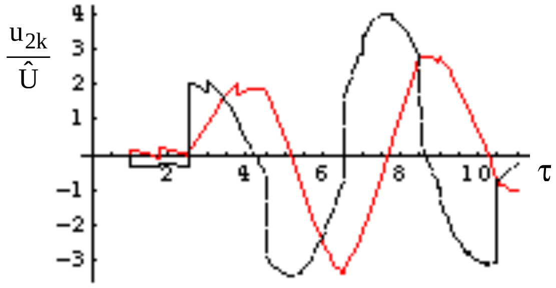


Example 1

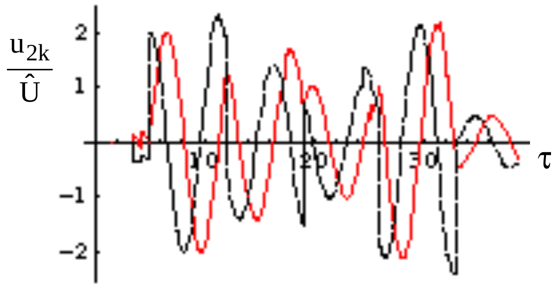


Example 2

Fig. 4 - Voltage at open line end, for simultaneous closure or all phases, in example conditions.

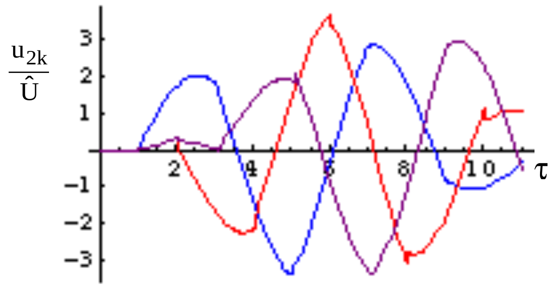


Example 1

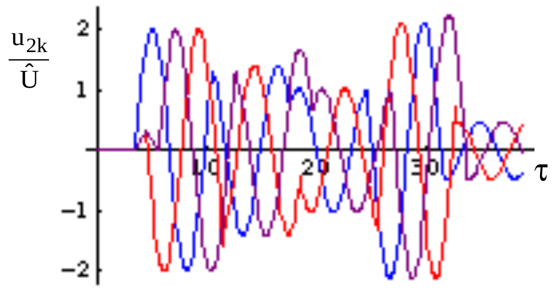


Example 2

Fig. 5 - Voltage at open line end, for the third phase to close, in example conditions.



Example 1



Example 2

Fig. 6 - Voltage at open line end, for synchronized switching on, in example conditions.

Of course, some more detailed and correct analysis should be done for real conditions, considering the frequency dependence of line parameters and consequent attenuation and distortion of wave propagation, and different propagation characteristics of several line modes. However, for simultaneous closing of all phases, when switching on the line, the error of the previous analysis has been found to be quite small, in several cases of very long lines treated with much more detailed and rigorous procedures. One reason for the small error arises from the fact that, for simultaneous closing of all phases, only the non homopolar line modes interfere in switching transients, and such modes are affected by frequency dependence, attenuation and distortion, much less than homopolar modes. So, all interfering modes correspond to a transient behavior not "too far" of ideal line conditions. Otherwise, even for transient conditions affected by homopolar modes, in very long lines, simplified analysis has been found to give approximate results, with some simple modifications of ideal line assumptions. The main reason for such behavior is that, along the total length of a very long line, homopolar components of high frequency are strongly attenuated. So, for some types of switching transients, a very detailed representation of phase-mode transformation dependence, and of frequency dependence of homopolar modes' parameters, can be avoided.

IV. TRANSMISSION LINE OPTIMIZATION

The transmission line should be optimized trying to obtain minimum total cost (including installation costs of line and associated equipment, and costs of operation, including losses) and maximum reliability in its operation in power system, taking into consideration several other aspects. Some characteristics of conventional transmission line projects are:

- Standardized bundles of conductors, with a symmetrical circular shape;
- High values for insulating distances.

These characteristics lead to lines with a limited parametric variation for each voltage level. So, the traditional line optimization process do not interfere very much with the equipment and network optimization. In this case, it is possible to not consider the transmission line optimization in a planning study.

It is possible to increase the characteristic power of a line by varying the bundle shape and by decreasing the insulation distances, which would be very interesting for very long transmission distances. The insulation distances can be reduced to low values with measures to reduce the overvoltages and the swing between phases. Some actions to decrease overvoltages are:

- Use of synchronized switching on of circuit breakers;
- Use of distributed arresters along the transmission line.

It is possible to reduce the swing between phases using insulated spacers.

Non-conventional transmission lines, on the contrary of traditional lines, have a high range of eventual variation of parameters. Some characteristics of five transmission line examples are shown in Table 1, where n_c is the number of conductors per bundle, D is the insulation distance, U_0 is the reference voltage (phase to phase for three-phase lines, phase to ground and between consecutive phases, for six-phase line), P_c is the characteristic power at voltage U_0, J_c is the current density with power P_c and voltage U_0. The geometric line configurations of these examples are presented in Fig. 7, 8 and 9. The examples are, respectively, a conventional 500 kV three-phase line, two non-conventional 500 kV three-phase lines, a non-conventional double-circuit three-phase line and a non-conventional six-phase line. In all these examples conductors have 483 mm^2 ("Rail"), and the electric field in air, with voltage U_0, is limited to 0.9 x 2.05 MV/m.

The non-conventional lines have reduced insulation distance and non standardized bundles of conductors. The bundle geometries were optimized by a computational program. The program maximizes the characteristic power of a line respecting a maximum electric field on conductors' surface and some geometric constraints of bundles' shape and location.

The characteristic power of the non-conventional 500 kV lines of examples 2 and 3 is much higher than that of the conventional 500 kV line (example 1). For a long distance transmission, the transmission power capacities of the non-conventional lines of examples 2 and 3 are greater than the double of the conventional line's capacity (example 1).

The three-phase double-circuit and the six-phase configuration allow to almost double the power capacity for long distance transmission, with a moderate increase of right of way area. The advantage of six-phase transmission is the possibility to decrease insulation distance, since the voltage phase-to-phase, for consecutive phases, is equal to the phase-ground voltage, and is less than in the case of three-phase double-circuit line. However, the optimized bundles for the six-phase line are greater than those of the three-phase double-circuit line.

The methodology of line optimization is shown in details in [7-10]. The electric compensation of line, the switching and operational criteria must be optimized together with the line. In item V. we present an example that illustrates the importance of joint optimization.

Fig. 10 illustrates the eventual impact of the non-conventional line, NCL, concept and and its results in line optimization. This Figure indicates the approximate range of characteristic power, $\mathbf{P_c}$, that can be obtained within prudent choices and criteria, without very special efforts. In Table II we indicate corresponding ranges for three base nominal voltages. It is feasible to project lines with characteristic power much higher than with traditional engineering practice, with optimized solutions, and with reduced ambient impact.

TABLE I - Main parameters of line examples

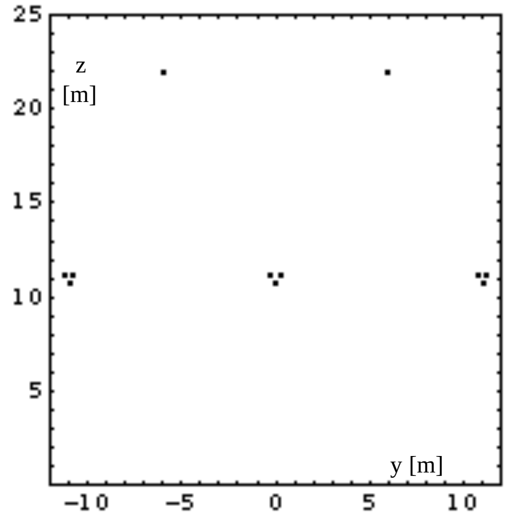
Example	D [m]	n_c	U_0 [kV]	P_c [MW]	J_c [A/mm^2]
1	11	3	500	924	0.736
2	5	6	500	1910	0.761
3	6	7	500	2295	0.783
4	7	5	$350\sqrt{3}$	4134	0.815
5	3	5	350	3955	0.779

V. IMPORTANCE OF JOINT OPTIMIZATION OF LINE, NETWORK AND OPERATIONAL CRITERIA

To illustrate the importance of joint optimization of compensation of line, switching and operational criteria, we describe briefly some aspects of a specific project [12-13, 23].

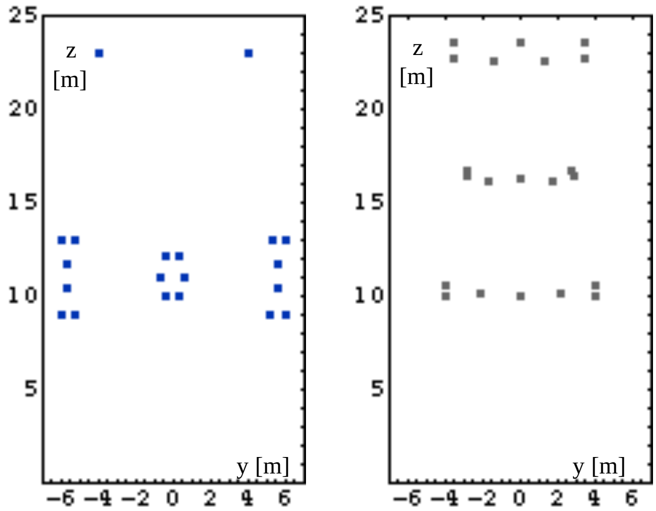
The analyzed transmission system is based on a 420 kV line, 865 km long, 50 Hz, with "non-conventional" concept, connecting Terminal 1 to Terminal 2. Its most important characteristics shown below :

- A 420 kV "non-conventional" transmission line conception. The structure is external to the three phases, which allows to reduce the distance between the phases and to obtain more adequate line characteristics for the transmission analyzed.
- Ground with frequency dependent parameters, being the conductivity at low frequencies around 0.5 mS/m.



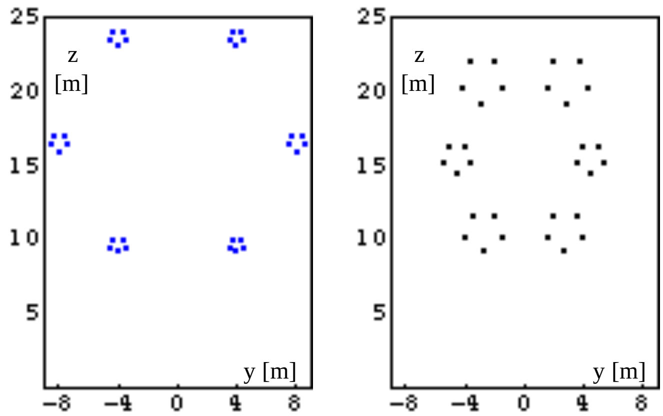
Example 1

Fig. 7 - Conventional transmission line of 500 kV.



Example 2 Example 3

Fig. 8 - Transmission lines of 500 kV , with non-conventional conductor bundles.



Example 4 Example 5

Fig. 9 - Double circuit three-phase and six-phase transmission lines, with non-conventional symmetric conductor bundles.

- Series compensation corresponds to 0.5 times the line's direct longitudinal reactance.
- Shunt compensation (for direct and inverse components) cor-

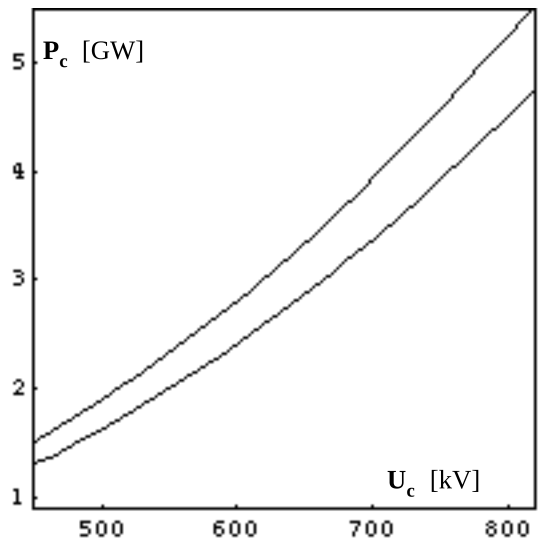


Fig. 10 - Characteristic power, $\mathbf{P_c}$, than can be obtained with optimized non-conventional lines (NCL) within prudent criteria, in function of voltage, $\mathbf{U_c}$ (phase-phase, rms), for three-phase lines.

TABLE II - Feasible range of $\mathbf{P_c}$, with optimized non-conventional three-phase lines (NCL), for three values of $\mathbf{U_c}$

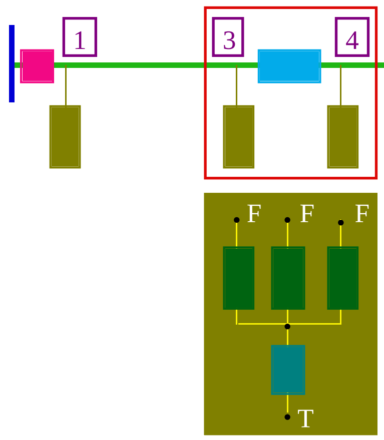
U_c [kV]	P_c [GW]
500	1.6 to 1.9
525	1.8 to 2.1
750	3.9 to 4.6

responds to 0.8 times the line's direct transversal admittance.

- Compensation system, both in series and shunt, as shown in Fig. 11, with a compensation installation in the middle of the line, as well as shunt compensation at both line terminals. It is worth mention that it is possible to have just one point of compensation along the line (besides the compensation at both line ends).
- Maximum eventual 800 MW load at Terminal 2.

Fig. 11 shows the basic transmission scheme, including the series and shunt compensation equipment. Fig. 12 shows, schematically, the line considered. This transmission system has some unfavorable constraints (e. g. 865 km), compared with "most common" transmission systems. In order to obtain an optimized solution, it was necessary to perform a systematic analysis covering a large number of options and parameters. With the study procedure used, a solution with a non-conventional line was found, in which it was possible to conciliate apparently contradictory requirements and constraints. This solution allowed a relatively low cost transmission system with good operational quality. Some interesting aspects of proposed transmission system are:

- There are reactive compensation only at line extremities and in an intermediate point.
- The 865 km transmission system is switched directly from one extremity, without switching at intermediate points.
- The line arrangement is optimized for the specific line length and transmitted power.



Symbol	Meaning
	Transmission line, with 865 km
	Bus-bar to which line is connected
	Line switching circuit breaker
	Shunt reactor (obtained with three phase reactors, one neutral reactor)
	Series capacitor
	Compensation system in middle of line
1 2 3 4	Points in which line is connected to compensation equipment

Fig. 11 – Line basic scheme, including series and shunt compensation system.

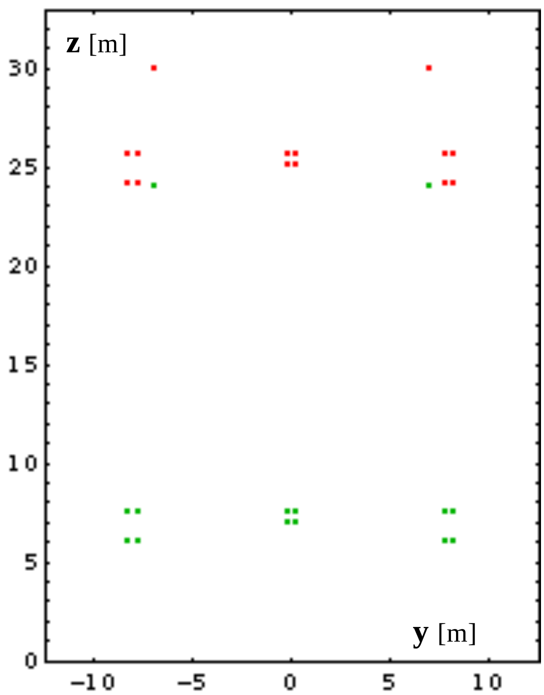


Fig. 12- Transmission line schematic representation. The green points represent the conductors at middle span, for a span 380 m and phase conductors at 60 ^{0}C . The red points represent the conductors near the structure.

- Single-phase opening and reclosing, assuring high probability of secondary arc extinction, for single phase faults, in order to obtain high reliability of transmission.
- Joint optimization of project and operational criteria, allowing important cost reduction.

VI. CONCLUSIONS

The paper presents the problem of AC transmission at very long distance, interpreting the dominant physical and technical phenomena, and using simulations to detail and confirm general analysis.

The paper shows that: electric transmission at very long distance is quite different of what would be expected by simple extrapolation of medium distance transmission experience; to optimize a very long distance transmission trunk, a more fundamental and open approach is needed. For example:

- Very long distance lines do not need, basically, reactive compensation, and, so, the cost of AC transmission systems, per unit length, e.g., for 2800 km, is much lower than, e.g., for 400 km.
- The choice of non-conventional line conception is appropriate for very long transmission systems, including eventually:
  - "Reduced" insulation distances, duly coordinated with adequate means to reduce switching overvoltages;
  - Non-conventional geometry of conductor bundles, six-phase lines, surge arresters distributed along the line.
- Switching transients, for several normal switching conditions, are moderate, in what concerns circuit breaker duties and network transients' severity, for lines and equipment. Namely, line energizing, in a single step switching, of a 2800 km line, without reactive compensation, originates overvoltages that are lower than, or similar to, overvoltages of a 300 km line with reactive compensation.
- There are some potentially severe conditions quite different from typical severe conditions in medium distance systems, e.g., in what concerns secondary arc currents, and requirements to allow fault elimination without the need of opening all line phases. The severity of such conditions is strongly dependent of circuit breaker and network behavior. Due to peculiar characteristics of long lines' transients, it is possible to reduce drastically the severity, with fast switching and appropriate protection schemes.
- Quite good results can be obtained with a careful coordination of circuit breakers with line and network, namely with synchronized switching, coordination of several circuit breakers and closing auxiliary resistors. Eventually, special schemes can be used to limit overvoltages for some quite unfavorable conditions of fault type and location.

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VIII. BIOGRAPHIES

Carlos Portela was born in 1935. Electrical Engineer (1958), IST - Superior Technical Institute, Lisbon Technical University, Doctor in Electrical Engineering (1963), IST. He was Cathedratic Professor at IST and worked in several countries, in major power systems projects, as consultant, and in power utilities, in research, system planning, equipment design and operation. Presently he is Titular Professor at COPPE / Federal University of Rio de Janeiro. His present main interests relate to power systems non-conventional technologies, study and modeling of transient phenomena and their consequences.

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