CIGRE SC 13

Florianópolis 1995 Colloquium

SOME ASPECTS OF VERY LONG LINES SWITCHING

C. Portela

1. Introduction

The practical experience of transmission lines with lengths of a few hundred kilometers or less indicates that, in such length range, the line switching severity increases with line length, either in what concerns circuit breaker duties for several switching conditions, or switching transients' severity, namely overvoltages, and consequent insulation requirements of line and connected equipment and surge arrester duties. As a consequence, in such range, it is normal the use of line compensation, shunt, series or both types. The extrapolation of this experience would lead to suppose that switching of very long transmission lines (length of about 2500 to 3000 km), as it is foreseen for electric transmission in Brazil, in future, from Amazonian Region to Southeast Region, would imply in quite severe switching problems and costly reactive compensation.

The problem of AC transmission at very long distance was studied in connection with some transmission system alternatives. A basic physical analysis lead to the conclusion that it would be wrong to extrapolate the classical solutions of medium distance (a few hundred kilometers) transmission, and that a more fundamental and open approach was needed, considering possible conceptions quite different of traditional medium distance systems. The problem was carefully studied, using several methods to consider the transmission system behavior, interpreting the dominant physical and technical phenomena, including circuit breaker interaction with the transmission system, and search of severe duties, in what concerns circuit breaker, line and connected equipment, and detailed simulations to detail and confirm general physical 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. By example:

- Very long distance lines do not need, basically, of 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.

- For very long transmission systems, it is appropriate the choice of non conventional line conception, including:
    - Characteristics of the type of lines usually designated by "high surge impedance loading" (although this terminology does not appears the most adequate), with low characteristic impedance at power frequency, and "reduced" insulation distances, duly coordinated with adequate means to reduce switching overvoltages and to obtain high reliability.
    - Within reasonable limits, non conventional solutions, by example: eventually non conventional conductors geometric location, eventually six-phase lines, eventually 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, overvoltages of a 300 km line with reactive compensation.

- 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.

- There are some potentially severe conditions, quite different from typical severe conditions in medium distance systems, namely in connection with some types of faults, in some ranges of line length. The severity of such conditions is strongly dependent of circuit breaker behavior. By example, due to peculiar characteristics of long lines' transients, it is possible to reduce drastically the severity by fast switching and appropriate protection schemes.

- It is convenient to adopt fast protection schemes, considering circuit breakers and fault detection aspects, procedures to extinguish secondary arc, and, eventually, special switching conceptions avoiding to trip the line for most frequent faults, e.g. non permanent single phase faults, and some special schemes to limit overvoltages for some quite unfavorable conditions of fault type and location.

- There are several conditions in which very long line systems behave in a quite different way of traditional systems, e.g., in what concerns secondary arc currents, and requirements to allow fault elimination without the need of opening all line phases. To allow system optimization and good operating conditions, careful analysis of circuit breaker behavior and requirements must be done, with adequate joint consideration of circuit breaker and network.

Due to the inexistence of practical experience of very long transmission lines, and 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, identifying special duties of equipment, including circuit breakers, and doing best use of circuit breakers and equipment, to increase reliability of transmission trunks.

The previous aspects arise some consequences for circuit breaker duties and requirements, that must be carefully evaluated.

Some results of published literature, that were not confirmed by our studies, would lead to quite special requirements of circuit breakers, namely for normal switching of very long lines. Our studies have shown that, on the contrary, most of normal switching conditions of very long lines, for adequate conception of transmission system, impose duties for circuit breakers that are similar or less severe than for traditional very high voltage networks. However, there are some requirements typical of very long lines, that must be considered with most care.

2. Main aspects of very long lines switching

In order to characterize the main aspects of very long lines switching, we present some results obtained in a detailed study of a six-phase alternative with 2800 km lines, nominal phase to ground voltage 500 kV, characteristic power 5544 MW, considering detailed line representation, including frequency dependence for the several propagation modes, phase transposition, and statistical simulation of elapsed time among closing time of six phases. Some results obtained in studies of three phase lines, for the same length and similar characteristic power, indicate that the main aspects presented above are quite similar for three and six phase lines.

For direct energisation, in a single step, of the line, without reactive compensation and without preinsertion resistors, the following results were obtained for "maximum" overvoltages at open end line terminal (obtained from a statistical sample of 100 switching simulations), phase to ground, and between consecutive phases (taking as unity, respectively, the amplitude of phase to ground and phase to phase voltages, at source side):

Surge arresters	Closure synchronization	Maximum overvoltage (pu)	
		Phase to ground	Phase to phase
No	No	2.20	2.70
Yes	No	1.81	1.93
No	Yes	1.92	1.92
Yes	Yes	1.74	1.73

For line switching off, without fault and without surge arresters, a maximum overvoltage phase to ground of 2.32 pu was obtained, without forced delay of phase opening, and 2.42 with forced delay. Between adjacent phases, maximum overvoltages were, respectively, 3.08 pu and 3.09 pu.

For single phase to ground fault, with systematic search of more severe location of fault, and point at which maximum overvoltage occurs, with single phase opening and reclosure, with and without fault extinction after first opening, the maximum overvoltages along the line, phase to ground and between consecutive phases, were:

Surge arresters	Maximum overvoltage (pu)	
	Phase to ground	Phase to phase
No	2.56	2.28
Yes	1.89	1.93

For faults among to alternate phases and ground (one of the more severe faults, for a six phase line), with systematic search of more severe location of fault, and point at which maximum overvoltage occurs, with three phase opening and reclosure, and with fault extinction after first opening, the maximum overvoltages along the line, phase to ground and between consecutive phases, were:

Surge arresters	Maximum overvoltage (pu)	
	Phase to ground	Phase to phase
No	4.95	5.72
Yes	1.94	2.33

For load rejection, with single phase and three phase opening and successful reclosure, without surge arresters, the maximum overvoltages, phase to ground, and between consecutive phases, were, approximately:

Type of switching	Maximum overvoltage (pu)	
	Phase to ground	Phase to phase
Single phase	2.32	2.97
Three phase	2.32	2.97

3. Single phase faults switching aspects

For very long lines, when a single phase to ground occurs, secondary arc current depends on fault location, and may be much higher than typical in traditional lines. So, the opening of circuit breakers in phase under fault is not enough to assure fault extinction. As single phase faults are the most probable ones, it is justified to take measures that avoid the opening of all phases, to eliminate the fault. In fact, the opening of all phases may be a severe disturbance for the network, whose probability must be quite reduced, to increase system reliability. The opening and subsequent reclosure of a single phase, if it allows elimination of most faults, would be a much less severe disturbance for the power system, that may be accepted to have a relatively higher probability.

In not very long transmission lines (lengths of a few hundred kilometers), the solution of this type of problem is based, typically, in an adequate choice of the ratio of homopolar reactance to non homopolar reactance of shunt reactors (e.g. with an additional neutral reactor in reactor banks). In traditional type networks, it is obtained, by this procedure, the limitation of secondary arc current to a small value, enough to assure, in most cases, the natural extinction of secondary arc.

In very long lines, however, a similar procedure would not allow a sufficient reduction of secondary arc current, due to fundamental physical reasons of line behavior. So, different type of measures must be adopted, to obtain secondary arc extinction and to allow single phase switching and elimination of most line faults without need of tripping all phases.

The connection of faulty phase terminals to ground, during such phase opening, through a passive impedance, is not enough to reduce secondary arc current to a value that assures its natural extinction. To allow secondary arc extinction, with single phase opening, actuating only at line terminals, it is necessary that at one of the phase terminals, active power is "injected" is faulty phase, or, what is a different interpretation of the same requirement, it is necessary that the "equivalent impedance" of the circuit connected to a faulty phase terminal behaves as an impedance with negative resistance.

In principle, several types of solutions are possible, to allow secondary arc extinction, without opening of non faulty phases, namely:

a - To use an auxiliary circuit, naturally of power electronics type, connected to faulty phase terminal during phase opening, behaving, as seen from such terminal, as an adequate impedance, with negative real part.

b - To adopt a special switching scheme that switches the faulty phase, after its disconnection, to an adequate voltage source, eventually obtained from auxiliary transformers or tertiary windings of main transformers, choosing and controlling the voltage of auxiliary source to reduce secondary arc current.

c - To adopt an auxiliary switching scheme, through which, during opening of faulty phase, such phase is connected to ground at some intermediate points, for a short time.

d - For the case of six phase lines, to adopt some special switching schemes, e.g. to disconnect also, from line terminals, the phase opposite to the faulty one, and connect both together, for a short time, before reclosure.

In order to arise to a convenient solution, based in any of these solution types, it is necessary some development work. Eventually, some simple switching equipment, without all the requirements of usual circuit breakers, would help to obtain a convenient solution for this problem.

Of coarse, if the requirements to allow secondary arc extinction with single phase opening, in case of single phase faults, do not allow an optimized solution, considered satisfactory, with actual technology, opening of all phases (for three phase lines), or, at least, more than one phase (for six phase lines) must be adopted, for single phase faults.

4. Multiphase faults switching aspects

In very long lines, for some ranges of fault location and some types of faults, very high overvoltages can occur, if no special measures are adopted to reduce overvoltages. The main reason of these very high overvoltages is that, for such conditions, it occurs a resonant type phenomena, and, for extreme cases, the sustained overvoltages are limited only by resistance parameters. Due to transmission power requirements, for very long lines, resistance parameters must be low, and, so, in some conditions, overvoltages, may be very high.

The most natural procedure to limit this type of overvoltages, is the adequate choice of characteristics and location of surge arresters. Different "levels" of surge arrester based solutions are possible, in connection with the joint optimization of insulation line levels, compactation level, cost and reliability.

In any case, it is convenient to adopt, complementary to surge arresters, some measures related to switching equipment, namely to reduce energy dissipated in surge arresters, and to reduce overvoltages, at least in a statistical view point.

To identify circuit breaker requirements, related to this problem, it is necessary to consider an important characteristic of these overvoltages, related to near resonant conditions in very long lines. In fact, when this high overvoltages occur, there is a relatively slow increase of the envolvent of successive relative maxima, as represented in a schematic way in figure 1. This behavior has a strong physical reason, that arises from the fact that, when fault occurs, voltage increase is associated to propagation and reflection of waves originated in the point of fault. The initial amplitude of such wave is of the order the peak value of normal line voltage, $\hat{U}$. The elapsed time for having a return effect, due to reflected wave, for very long lines and the most severe conditions, is of the order of the period, T_f , at power frequency (for 60 Hz, T_f = 16.7 ms). The evolution of voltage, in most severe conditions, is, so, similar to an escalation of $\hat{U}$ at time intervals equal to T_f , till overvoltages approach the resonant limit value (in the surge interpretation, this same limitation is obtained considering the attenuation of waves during propagation, approximately in geometric progression with time, after a few reflections).

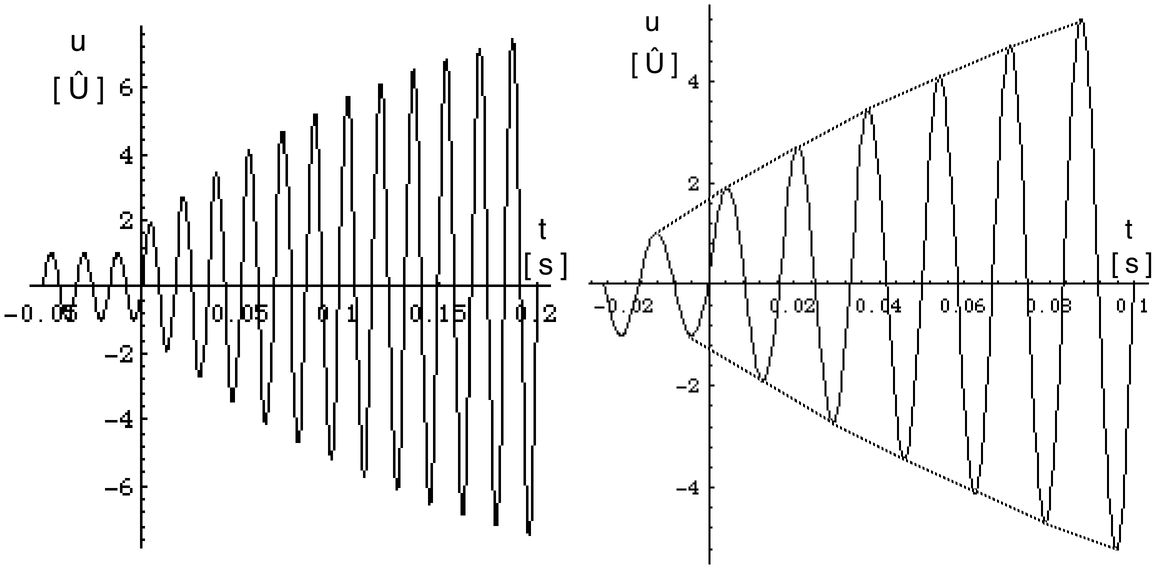


Fig. 1 - Basic form of overvoltages associated to unfavorable fault location and fault type, for very long lines.

It is worth to mention that this type of behavior was obtained, systematically, in detailed simulations of severe overvoltage conditions, in 2800 km lines, considering modal analysis, frequency dependence of line parameters, several fault types and fault locations (some published results may be found in reference 7).

This type of behavior, of overvoltages in very long lines, for conditions for which very high overvoltages occur, have important consequences.

The first aspect is related to the shape of very high overvoltages and recovery voltages that circuit breakers must support, if no measures are taken to limit drastically such overvoltages. This shape is quite different of usual specification of recovery voltages. Essentially, at line side of circuit breaker, the voltage is "modulated" with a slope of the order of $S_f = f\,\hat{U}$.

The second aspect relates to the use of circuit breakers to reduce such high overvoltages. As voltage increase is relatively slow, fast actuation of circuit breakers allow important reduction of maximum overvoltages. Roughly, maximum overvoltage is a linear function of elapsed time , ν, between fault and effective opening of circuit breaker. A reduction T_f of ν , allows a reduction of maximum overvoltage of the order of $\hat{U}$ (for conditions of severe overvoltages in very long lines, and for overvoltages non limited by surge arresters).

It is also necessary to consider that, for very long lines, the propagation of fault effects along the line, and the propagation of protection or control signals, between terminals, is non negligible (at least 9.3 ms for a 2800 km line). Also, relays based in power frequency magnitudes, for fault identification, have an inherent delay to correctly identify line faults and give correct and protection orders. To reduce this physical inherent delay, it is necessary to base fault identification in line transient behavior, and not in a power frequency interpretation of voltages and currents.

It is important, for very long lines, to have circuit breakers, relays and protection schemes, that assure very fast circuit breaker operation in fault conditions that might be associated to very high overvoltages. The correct optimization of very long distance transmission systems must consider the real possibilities of circuit breakers, relays and protection schemes, and its effect in overvoltage reduction.

5. 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, 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.

Let us assume that the line behaves like an ideal line, without losses (as if line conductors and soil would have infinite conductivity). In such a case, surges would propagate, along the line, without attenuation and distortion, and all line modes would propagate with the same speed, v (equal to speed of electromagnetic waves in air). Also, per unit length inductance and capacitance matrices, L , C , e.g. in phase coordinates, would be inverse matrices, apart a scalar factor, being

$L\ C = v^{-2}\ |1|$ (|1| unitary matrix, with diagonal elements equal to 1 and non diagonal elements equal to 0)

$Z = \sqrt{L\ C^{-1}} = v\ L$ (Z surge impedance matrix)

$Y = Z^{-1} = v^{-1}\ C$ (Y surge admittance matrix)

So, without faults at intermediate line points, the voltages, u_1 , u_2 , and currents, i_1 , i_2 , at line terminals, 1 , 2 (being u_1 , u_2 , i_1 , i_2 , matrices of corresponding phase coordinates) can be expressed by

$u_1 = u_p(t) + u_n(t)$ $\qquad$ $i_1 = Y\ u_p(t) - Y\ u_n(t)$

$u_2 = u_p(t - T) + u_n(t + T)$ $\qquad$ $i_2 = Y\ u_p(t - T) - Y\ u_n(t + T)$

being $u_p(t)$ the matrix of positive wave voltages, $u_n(t)$ the matrix of negative wave voltages, both at terminal 1 and in phase coordinates, and T the propagation time along line length L ($T = L / v$).

So, when switching on the line, at terminal 1, with terminal 2 open, from a zero voltage condition, and without faults at intermediate line points,

$i_2 = 0 \ \rightarrow\ u_n(t) = u_p(t - 2\ T)$

$u_1 = u_p(t) + u_p(t - 2\ T)$ $\qquad$ $i_1 = Y\ u_p(t) - Y\ u_p(t - 2\ T)$

$u_2 = 2\ u_p(t - T)$

Let us assume that the line is energized from an "infinite" busbar (whose voltage is not affected by line switching), whose voltage is u_0 [matrix of phase to ground voltages, $u_{0k} = g_k(t)$, at such busbar, being k the phase index (k = 1 , 2 , 3 for a three-phase network)], with a circuit breaker without pre-insertion resistors.

The condition at terminal 1 , at phase k , is:
- Before the closure of phase k energizing circuit breaker, $i_{1k} = 0$.
- After closure, $u_{1k} = u_{0k} = g_k(t)$.

Let us consider, first, the hypothesis of simultaneous closure of all phases, at instant $t = 0$.

In such case,

for $t < 0$ $u_{1k} = 0$
for $t > 0$ $u_{1k} = g_k(t)$

and, so,

for $0 < t < 2\,T$ $u_{pk}(t) = g_k(t)$

for $2\,T < t < 4\,T$ $u_{pk}(t) = g_k(t) - g_k(t - 2\,T)$

for $4\,T < t < 6\,T$ $upk(t) = g_k(t) - g_k(t - 2\,T) + g_k(t + 4\,T)$

for $6\,T < t < 8\,T$ $u_{pk}(t) = g_k(t) - g_k(t - 2\,T) + g_k(t - 4\,T) - g_k(t - 6\,T)$

…

for $t < T$ $u_{2k}(t) = 0$

for $T < t < 3\,T$ $u_{2k}(t) = 2\,g_k(t - T)$

for $3\,T < t < 5\,T$ $u_{2k}(t) = 2\,[\,g_k(t - T) - g_k(t - 3\,T)\,]$

for $5\,T < t < 7\,T$ $u_{2k}(t) = 2\,[\,g_k(t - T) - g_k(t - 3\,T) + g_k(t - 5\,T)\,]$

for $7\,T < t < 9\,T$ $u_{2k}(t) = 2\,[\,g_k(t - T) - g_k(t - 3\,T) + g_k(t - 5\,T) - g_k(t - 7\,T)\,]$

…

Let us assume that

$g_k(t) = \hat{U} \cos(\omega\,t + a)$ (a depending on switching instant, taken as $t = 0$, and on phase considered, defined by k , and being $\hat{U}$ the amplitude of phase to ground voltage at busbar)

In order to simplify analytical treatment, let us consider complex representation of sinusoidal voltages (in limited time intervals, during which the voltage is sinusoidal). Representing with bold characters complex parameters or time functions, we can made

$g_k(t) = \Re\,[\,\mathbf{g}_k(t)\,]$ $\mathbf{g}_k(t) = \mathbf{U}_k\,e^{i\,\omega\,t}$ $\mathbf{U}_k = \hat{U}\,e^{i\,a}$

$u_{2k}(t) = \Re\,[\,\mathbf{u}_{2k}(t)\,]$ $\mathbf{u}_{2k}(t) = \mathbf{U}_{2k}\,\mathbf{h}_k(t)\,e^{i\,\omega\,t}$ $\mathbf{U}_{2k}(t) = 2\,\mathbf{U}_k\,e^{-\,i\,\omega\,T}$

$b = \omega\,2\,T = 2\,\theta$ $\omega = 2\,\pi\,f$ (f power frequency)

$\theta = \omega\,T = \dfrac{\omega}{v}\,L$ θ "electric length" of line (in radians) at power frequency

$t < T$ $\mathbf{h} = 0$

$T < t < 3\,T$ $\mathbf{h} = 1$

$3\,T < t < 5\,T$ $\mathbf{h} = 1 - e^{-\,i\,b}$

$5\,T < t < 7\,T$ $\mathbf{h} = 1 - e^{-\,i\,b} + e^{-\,i\,2\,b}$

$7\,T < t < 9\,T$ $\mathbf{h} = 1 - e^{-\,i\,b} + e^{-\,i\,2\,b} - e^{-\,i\,3\,b}$

…

In each time interval, **h** is the sum of n terms in geometric progression, with a ratio, **r** , between two consecutive terms

$\mathbf{r} = -\,e^{-\,i\,b} = -\,e^{-\,i\,2\,\theta}$

So

$\mathbf{h} = 1 + \mathbf{r} + \mathbf{r}^2 + \mathbf{r}^3 + \mathbf{r}^4 + \mathbf{r}^5 + \mathbf{r}^6 + \mathbf{r}^7 + \mathbf{r}^8 + \mathbf{r}^9$

considering, in the sum, at successive time intervals, 0 , 1 , 2 , 3 , … terms.

The sum with n terms (for $n \geq 0$) is

$$\mathbf{S}_n = \left| \frac{1-r^n}{1-r} \right|$$

Considering arbitrary switching time instants (without synchronization of switched circuit breaker), the partial maximum switching overvoltage $Max_n[u_{2k}(t)]$ of $u_{2k}(t)$ (maximum value of $u_{2k}(t)$ obtained in each time interval, varying closing instant), in time interval $(2n-1)T < t < (2n+1)T$, is

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

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

$$Max[u_{2k}(t)] = S^{*}_{max}\, \hat{U} \qquad\qquad S^{*}_{max} = 2\,|\sec\theta|$$

In figure 2, some of the relative maximum coefficients, S^{*n}_{max}, and the global maximum coefficient, S^{*}_{max}, are represented, in function of electric line length, θ .

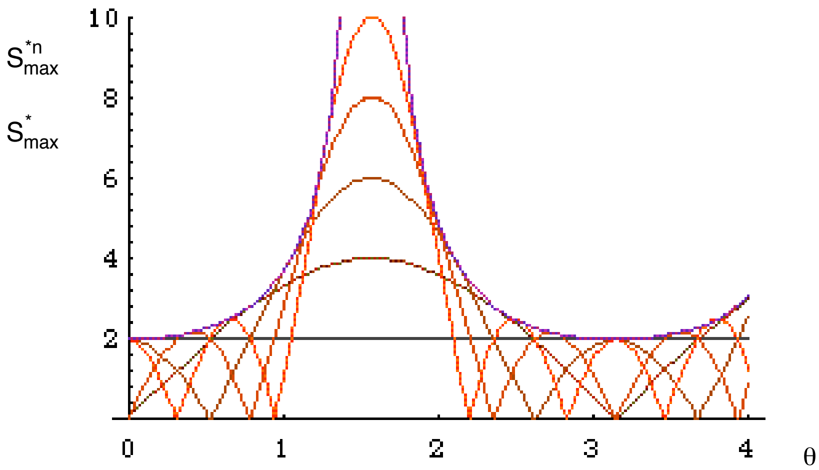


Fig. 2 - Coefficients S^{*n}_{max} and S^{*}_{max}, in function of line electric length, θ .

At power frequency, f , the considered ideal line has an equivalent π scheme, as represented in figure 3. For complex representation of sinusoidal voltages and currents, at line terminals,

$$\mathbf{Z}_e = Z \sinh(i\,\theta) = i\,Z \sin\theta \qquad\qquad \frac{\mathbf{Y}_e}{2} = Z^{-1}\tanh\left(i\,\frac{\theta}{2}\right) = i\,Y\tan\frac{\theta}{2} = i\,Z^{-1}\tan\frac{\theta}{2}$$

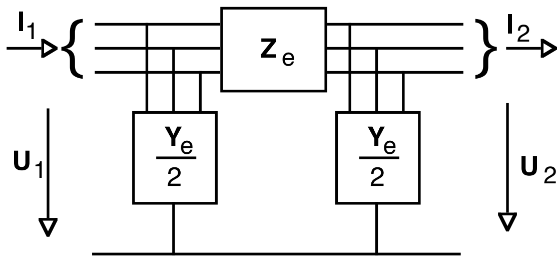


Fig. 3 - Equivalent π scheme of an ideal line.

So, with line open at terminal 2 (no load), in sinusoidal stabilized conditions,

$$\hat{U}_2 = \hat{U}_1\,|\sec\theta|$$

and the ratio of voltage amplitudes, at line terminals, is

$\hat{U}_2 / \hat{U}_1 = |\sec \theta|$

So, for the ideal line, with simultaneous closure of all phases, when switching on the line, from an "infinite" busbar, the maximum peak overvoltage, at line open end, is "exactly" twice the open end voltage at stabilized line conditions (after transient conditions).

Also, in such 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.

For an "exactly ideal" line, $v \cong 300$ m/μs . For a very high voltage line, the phase velocity, for non homopolar modes, at power frequency, is typically of the order of 294 to 297 m/μs . Assuming, for more easy interpretation of orders of magnitude, v =297 m/μs , being θ expressed in radians and L in km, we have

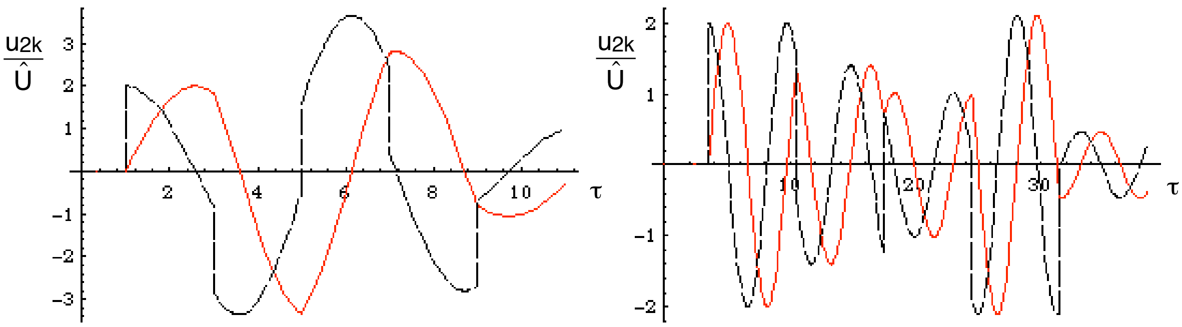
at 60 Hz $\quad L \cong 788 \text{ km} \,.\, \theta \qquad$ at 50 Hz $\quad L \cong 945 \text{ km} \,.\, \theta$

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 $S^{*,max}$ values are, respectively, 3.70 and 2.14 .

In figure 4 we represent, for these two examples, 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 $S^{*,max}$ formula.

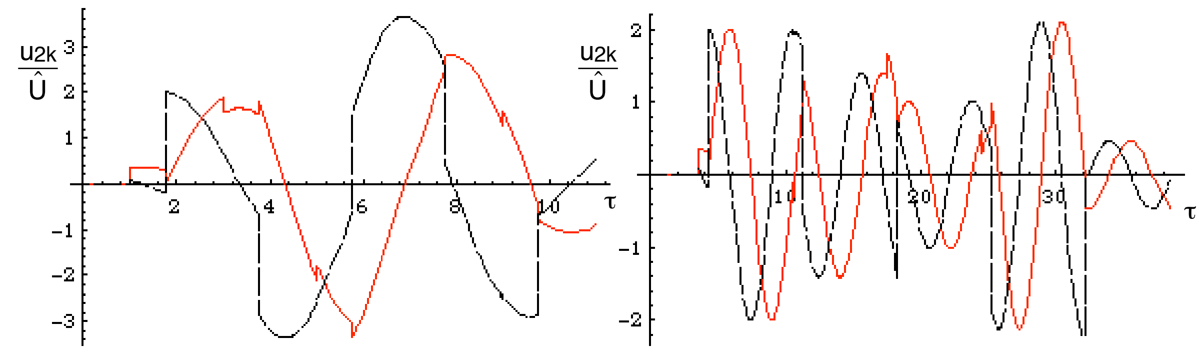
In order to consider non simultaneous switching of phases, a similar procedure can be adopted. It is necessary to consider, separately, terminal conditions of each phase, at closing side terminal. For instance, let us assume an ideal line, with diagonal elements of matrix Y having a value Y_p , and non diagonal elements a value Y_m ,, "infinite power" source at closing terminal , three phase line, closing instants of phases 1 , 2 , 3 , respectively 0 , $T_2 > 0$, $T_2 + T_3$, with $T_2 < T_2 + T_3 < 2\,T$, and phase to ground voltages, at source side, respectively, $g_1(t)$, $g_2(t)$, $g_3(t)$. In such conditions, phase to ground voltages of positive wave, at closing line terminal, $u_{pk}(t)$, for successive time intervals, have the analytical expressions indicated in table1 . The phase to ground voltage, at open end terminal, of phase k , u_{2k} , are related to u_{pk} by $u_{2k}(t) = 2\ \ u_{pk}(t - T)$. In very high voltage lines, the ratio Y_m / Y_p has values in the approximate range [-0.2 , -0.1] . For examples 1 and 2, we have assumed $Y_m / Y_p = - 0.15$.



Example 1 Example 2

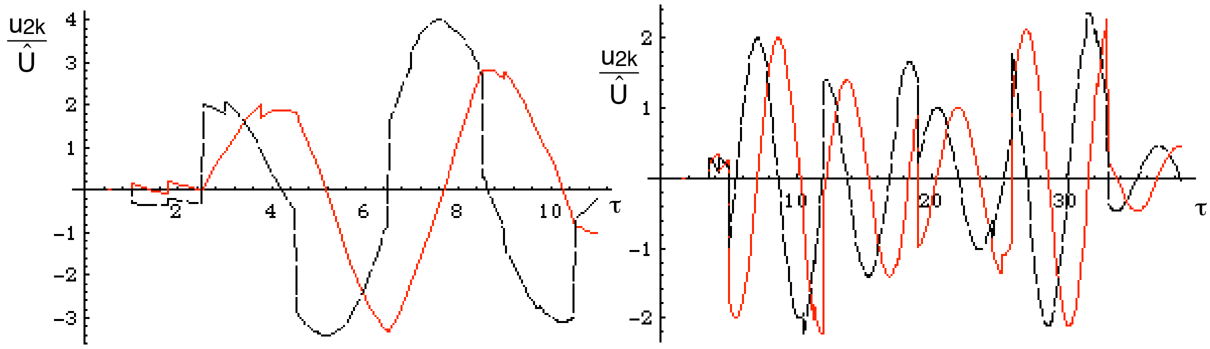
Fig. 4 - Voltage at open line end, for simultaneous closure or all phases, in example conditions.

In previous assumptions, voltage at open line terminal, for first phase to close, is not affected by posterior closing instants of other phases, etc. . For illustrative purposes, we represent, in figure 5 and 6, for examples 1 and 2, voltage in second and third phases to close, for T_2 = 2 ms , T_3 = 2 ms . In each figure, the two curves correspond to closing instants, of phase whose voltage is represented, at source side, zero and maximum. These curves, if compared with those of figure 4, illustrate the order of magnitude of switching overvoltage increase, that results of differences among closing instants in three phases.



Example 1 Example 2

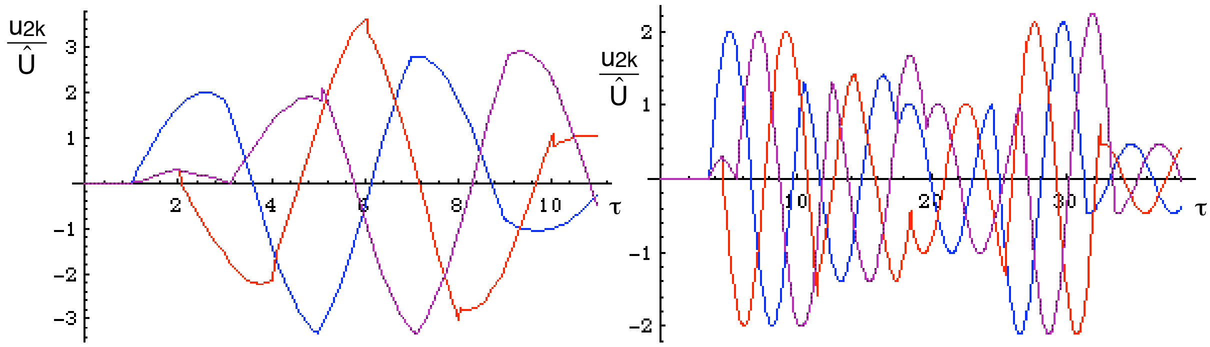
Fig. 5 - Voltage at open line end, for second phase to close, in example conditions.



Example 1 Example 2

Fig. 6 - Voltage at open line end, for third phase to close, in example conditions.

In figure 7, we represent, for examples 1 and 2, voltages to ground in three phases of open end line terminal, for synchronized switching on. Comparison of this curves with those of figures 5 and 6, illustrates the order of magnitude of switching overvoltage reduction that results of synchronized switching on.



Example 1 Example 2

Fig. 7 - Voltage at open line end, for synchronized switching on, in example conditions.

The curves of figure 2, in the range of $\theta \le \pi/2$, express the well known fact that line energization has an increasing severity with line length, what 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 line and reactive compensation, together, and, so reduce switching overvoltages. The range $\theta \ge \pi/2$ of those curves express, in a similar way, the main severity aspects of line energization, 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 is "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.

Table 1 - Positive waves, at closing line terminal, for closing sequence 1 , 2 , 3 , closing times 0 , T_2 , T_3 , with $T_3 < 2\,T$, in assumed conditions and being m the ratio between mutual and self “equivalent” wave coefficients

Time interval	Positive waves, $u_{pk}(t)$, at closing line terminal, for closing sequence 1 , 2 , 3		
$t < 0$	$u_{p1}(t) = 0$	$u_{p2}(t) = 0$	$u_{p3}(t) = 0$
$0 < t < T_2$	$u_{p1}(t) = g_1(t)]$	$u_{p2}(t) = -\,m\,g_1(t)$	$u_{p3}(t) = -\,m\,g_1(t)$
$T_2 < t < T_3$	$u_{p1}(t) = g_1(t)$	$u_{p2}(t) = g_2(t)$	$u_{p3}(t) = -\,m\,[\,g_1(t) + g_2(t)$
$T_3 < t < 2\,T$	$u_{p1}(t) = g_1(t)$	$u_{p2}(t) = g_2(t)$	$u_{p3}(t) = g_3(t)$
$2\,T < t < 2\,T + T_2$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T)$	$u_{p2}(t) = g_2(t) + m\,g_1(t - 2\,T)$	$u_{p3}(t) = g_3(t) + m\,g_1(t - 2\,T)$
$2\,T + T_2 < t < 2\,T + T_3$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T)$	$u_{p3}(t) = g_3(t) + m\,[\,g_1(t - 2\,T) + g_2(t - 2\,T)\,]$
$2\,T + T_3 < t < 4\,T$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T)$
$4\,T < t < 4\,T + T_2$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T) + g_1(t - 4\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T) - m\,g_1(t - 4\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T) - m\,g_1(t - 4\,T)$
$4\,T + T_2 < t < 4\,T + T_3$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T) + g_1(t - 4\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T) + g_2(t - 4\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T) - m\,[\,g_1(t - 4\,T) + g_2(t - 4\,T)\,]$
$4\,T + T_3 < t < 6\,T$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T) + g_1(t - 4\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T) + g_2(t - 4\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T) + g_3(t - 4\,T)$
$6\,T < t < 6\,T + T_2$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T) + g_1(t - 4\,T) - g_1(t - 6\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T) + g_2(t - 4\,T) + m\,g_1(t - 6\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T) + g_3(t - 4\,T) + m\,g_1(t - 6\,T)$
$6\,T + T_2 < t < 6\,T + T_3$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T) + g_1(t - 4\,T) - g_1(t - 6\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T) + g_2(t - 4\,T) - g_2(t - 6\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T) - g_3(t - 6\,T) + m\,[\,g_1(t - 6\,T) + g_2(t - 6\,T)\,]$
$6\,T + T_3 < t < 8\,T$	$u_{p1}(t) = g_1(t) - g_1(t - 2\,T) + g_1(t - 4\,T) - g_1(t - 6\,T)$	$u_{p2}(t) = g_2(t) - g_2(t - 2\,T) + g_2(t - 4\,T) - g_2(t - 6\,T)$	$u_{p3}(t) = g_3(t) - g_3(t - 2\,T) + g_3(t - 4\,T) - g_3(t - 6\,T)$
…	…		

The main objective of the previous analysis is to identify and explain the dominant physical aspects of line energization, 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, originate 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 several transient phenomena, including those associated to several types of faults and secondary arc aspects for single phase faults.

Of coarse, 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, till 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.

6. Summary and conclusions

The studies presented in paper have shown that electric transmission at very long distance (length of about 2500 to 3000 km, for transmission systems being studied in Brazil) is quite different of what would be expected by simple extrapolation of medium distance transmission experience. By example:

- Very long distance lines do not need, basically, of reactive compensation.

- For very long transmission systems, it is appropriate the choice of non conventional line conception, including types mentioned in the paper.

- 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.

- 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.

- There are some potentially severe conditions, quite different from typical severe conditions in medium distance systems, namely in connection with some types of faults, in some ranges of line length. The severity of such conditions is strongly dependent of circuit breaker behavior. By example, due to peculiar characteristics of long lines' transients, it is possible to reduce drastically the severity by fast switching and appropriate protection schemes.

- It is convenient to adopt fast protection schemes, considering circuit breakers and fault detection aspects, procedures to extinguish secondary arc, and, eventually, special switching conceptions avoiding to trip the line for most frequent faults, e.g. non permanent single phase faults, and some special schemes to limit overvoltages for some quite unfavorable conditions of fault type and location.

- There are several conditions in which very long line systems behave in a quite different way of traditional systems, e.g., in what concerns secondary arc currents, and requirements to allow fault elimination without the need of opening all line phases. To allow system optimization and good operating conditions, careful analysis of circuit breaker behavior and requirements must be done, with adequate joint consideration of circuit breaker and network.

- The main aspects of very long lines switching, including those, namely for normal switching, for which very long lines present favorable behavior, concerning circuit breaker requirements and duties, and some others, for which requirements are quite different of those of conventional networks, are presented in the paper.

References

1 - Portela, C. - Long Distance Transmission Using Six-Phase Systems - Proceedings II Symposium of Specialists in Electric Operational and Expansion Planning (Brazil), paper SP-48 , 14 p. , 1989

2 - Portela, C. ; Tavares, M. - Behavior and Optimization of a Six-Phase System for Normal Operation and Transient Phenomena - Proceedings XII National Seminar of Electric Energy Transmission and Distribution (Brazil), Oct. 1991 (in Portuguese)

3 - Tavares, M. - Six-Phase Transmission Line . Propagation Characteristics and Line Performance at Power Frequency and Electromagnetic Transients - M.Sc. Thesis, 820 p. (in Portuguese), COPPE/UFRJ (Brazil), 1991

4 - Portela, C. ; Tavares, M. - Six-Phase Transmission Line . Propagation Characteristics and New Three-Phase Representation - IEEE transactions on Power Delivery - Vol. 8, N. 3 , July 1993, pp1470-1483

5 - Portela, C. ; Moreno, G. ; Tavares, M. - Advantages of Six-Phase Transmission as Compared with Three-Phase Transmission Concerning Environmental Impact - Proceedings VIII International Symposium on High Voltage Engineering (Japan), Aug. 1993

6 - Portela, C. ; Tavares, M. ; Azevedo, R. - A New Line Representation for Transient Studies . Application to a Six-Phase Transmission Line - Proceedings VIII International Symposium on High Voltage Engineering (Japan), Aug. 1993

7 - Portela, C. ; Tavares, M. ; Azevedo, R. - Transient Phenomena in Very Long Lines . Application to Six-Phase Lines - Proceedings XII National Seminar of Electric Energy Transmission and Distribution (Brazil), Oct. 1993 (in Portuguese)

8 - Portela, C. ; Tavares, M. ; Moreno, G. - Basic Aspects of Very Long Distance Transmission - Proceedings XII National Seminar of Electric Energy Transmission and Distribution (Brazil), Oct. 1993 (in Portuguese)

Author's address

R. Eng. Cesar Grillo, 249, Barra da Tijuca, Rio de Janeiro, RJ, CEP 22640-150, Brazil
Phone: 55 - 21 - 4934201
Fax: 55 - 21 - 4934201