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I. ESSENTIAL ASPECTS OF VERY LONG DISTANCE TRANSMISSION

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]:

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

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:

$$\mathbf{Z}_c = \sqrt{\frac{\mathbf{X}}{\mathbf{Y}}} \qquad\qquad \mathbf{P}_c = \frac{\mathbf{U_0}^2}{\mathbf{Z_c}} \qquad (2)$$

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:

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

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:

$$\mathbf{U}_2 = \mathbf{U}_0 \qquad\qquad \mathbf{U}_1 = \mathbf{U}_0 \; e^{i\,\boldsymbol{\alpha}} \tag{5}$$

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, **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.

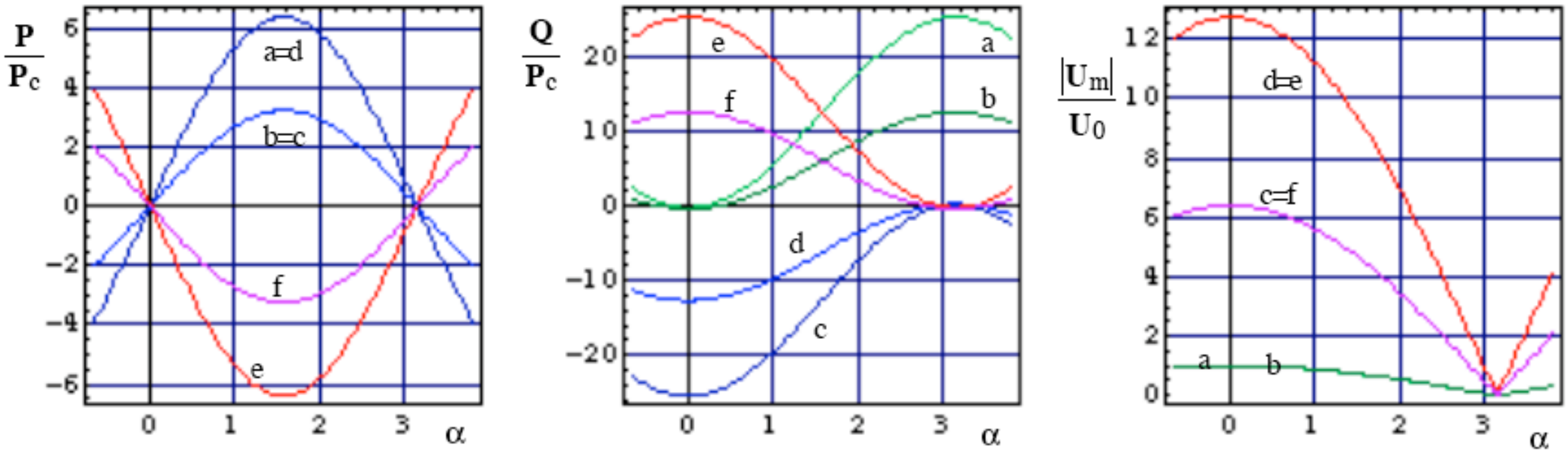

Fig. 1 - Transmitted power, **P**, reactive power absorbed by the line, **Q**, modulus of voltage at middle of the line, $|\mathbf{U}_m|$, in function of α, for six examples.

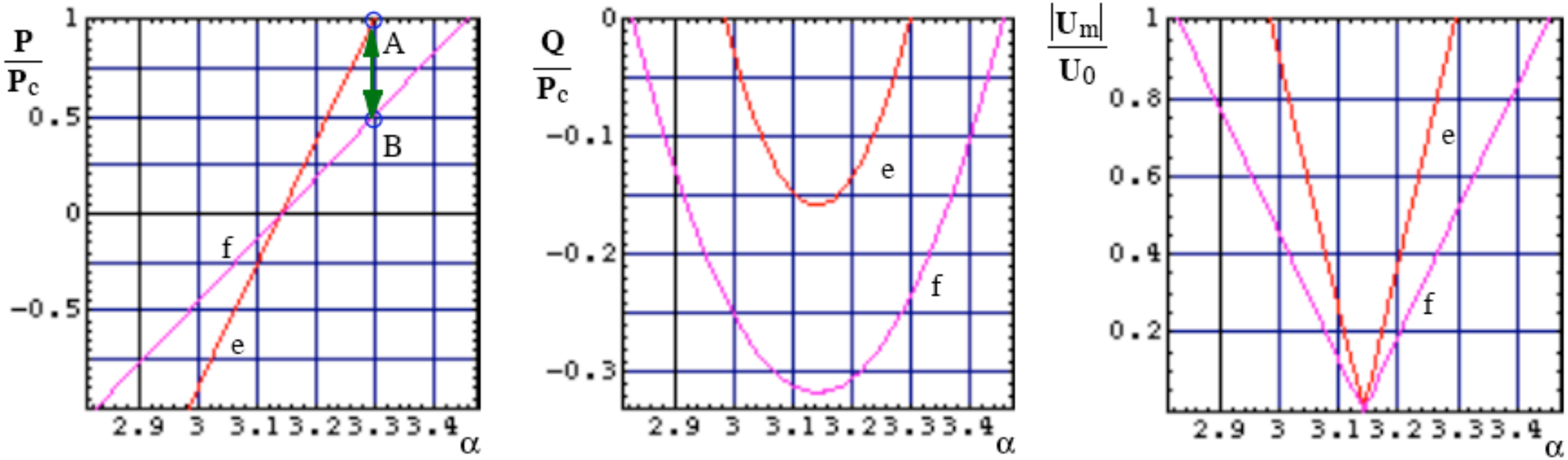

Fig. 2 - Transmitted power, **P**, reactive power absorbed by the line, **Q**, modulus of voltage at middle of the line, $|\mathbf{U}_m|$, in function of α , for two examples of very long lines, in normal operating range.

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 $-\mathbf{P}_c \leq \mathbf{P} \leq \mathbf{P}_c$. 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 $1.05\ \pi \leq \Theta \leq 1.10\ \pi$ is a reasonable first approach. Also for "slow" and "fast" transient behavior, this choice has very important advantages, as discussed below.

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).

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III. BASIC PHYSICAL ASPECTS OF VERY LONG LINES SWITCHING

IV. TRANSMISSION LINE OPTIMIZATION

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

VI. CONCLUSIONS