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Effect of Series and Parallel Compensation on Internal Transients in Overhead Transmission Lines

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ABSTRACT. The main parameters of transient phenomena in a line are analyzed. Both attenuation factor and propagation coefficient are investigated in the time domain for transient as well as for steady-state operation. A theoretical base for the proposed model is presented. The insulation-level dependence for overhead transmission lines is discussed for both transmission and distribution systems. The margin of this dependence is deduced according to the geometrical dimensions of conductors. Both capacitive and inductive compensation are inserted. The proposed algorithm reduces the computational time due to its simplicity even in lines with compensation. The dependence of the rate of rise of front voltage on series and parallel compensation is considered. The rate of rise of front voltage (RRFV) along a typical 750 kV 400 km line is evaluated. The dependence of the maximum value of RRFV on either the series-compensation rating or the shunt compensation at the receiving end of a typical 750 kV transmission line with different lengths is discussed.

Different electric power networks in many countries have been connected together, particularly in Europe. Arab countries should also consider inter connecting their national networks. Later, this may be connected with the European Power System. The final conjectured picture may be a large single international network.

However, the connection between national electric networks should be implemented across borders so that the two last substations in each country are

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Key Words: Transient, transmission lines, reactive, compensation, propagation, distribution, distortion.

connected through a long-distance UHV transmission line. This would enable a large bulk of power to be transmitted from one country to another, at the peak period of the other. This leads to economical utilization and operation of the international Arabic network in order to supply a load at its location. This is especially true when there is a difference between the local times of the countries concerned.

Since the insulation is the most expensive part of a line, the switching transients in UHV lines appear to be one of today's major problems. In EHV and UHV transmission systems, the switching processes create transient voltages which may exceed the value of lightning surges. Consequently, the design of EHV and UHV transmission systems should be based on internal overvoltages. Here, the phenomenon of switching transients on a compensated and uncompensated unloaded UHV line must be studied.

Transmission lines are the most complicated component in power systems when investigating electromagnetic transients. This is on account of the distributed characteristics of line elements, such as inductance L, resistance R, shunt capacitance C and conductance Go. The earth may be taken as homogeneous and line parameters will consequently be frequency dependent (Hamed and Esmail 1994).

Consideration of the earth effect (either homogeneous or non-homogeneous) while calculating transients in transmission lines means that the line parameters defined above do not have constant values but vary nonlinearly. Since the apparent nonlinear line parameters render the evaluation of transients more complicated, it is convenient to approximate the nonlinear elements of a line as a certain number of T or π equivalent-circuit sections. General criteria for selecting the number of equivalent T or π sections required for accurate representation of a line over the range of frequency of interest have been proposed (Muller and Quintana 1989).

The problem of transients is particularly significant for long lines as well as for those including external compensation (series, or parallel or both). This justifies further investigation of external compensation under different conditions in order to determine the optimal conditions for design or operation.

Problem Formulation

Typical transmission lines operated in the range 110 – 750 kV are studied from the point of view of geometry of phases. The relationship between nominal operating voltage and the spacing as well as with the height of conductors for these lines is calculated. The results are drawn in Fig. 1(a) and Fig. 1(b) as a ratio of the spacing between phases D (including the mirror effect) to the average spacing d.

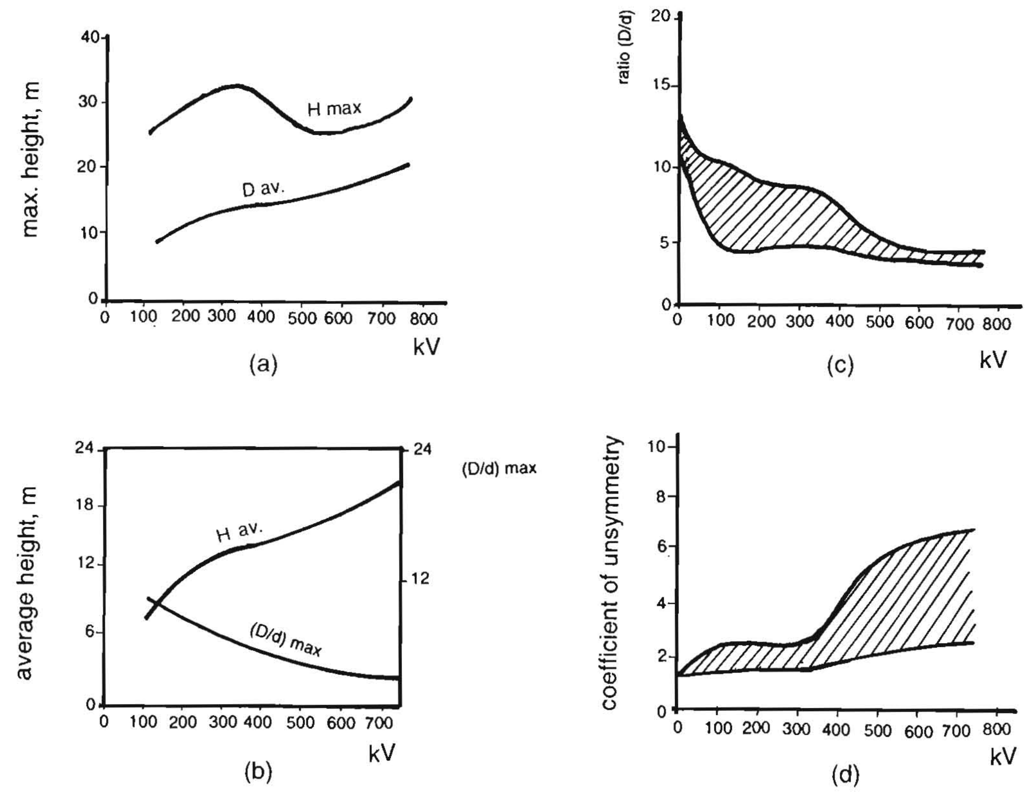


Fig. 1. The geometrical line characteristics and operating voltages.
(a) Maximum height and average spacing.
(b) Average height and spacing ratio.
(c) The dependence of spacing ratio and its variation margin on nominal voltage.
(d) Dependence of coefficient of asymmetry on nominal voltage for non-transposed lines.

The large values of the ratio (D/d) correspond to the case of low-voltage transmission (*i.e.* a distribution system), while the small values correspond to EHV and UHV overhead lines (i.e. the transmission systems). More typical transmission lines are considered giving the margin of variation of the maximum ratio (D/d) as shown in Fig. 1(c). In this case, the low voltage level is considered with different approximate values. All dimensions are taken from (Hamed and Papadopoulos 1989). The maximum ratio D/d for distribution systems is varied between 18.2 and 6.25 for voltages from 10 to 35 kV.

The dependence of the coefficient of asymmetry k (caused by the non-transposition of phases) on the voltage is illustrated in Fig. 1(d). These characteristic curves indicate that the effect of earth return increases with rise in the nominal voltage of operation. Thus, introducing the frequency-dependent parameters appears to be an important factor in calculating of transients in transmission lines. A technique containing the frequency-dependent effect of a transformation matrix is automatically taken into account. A comprehensive investigation of phase-to-phase switching surges on a 500 kV unloaded transmission line is necessary using digital computers. Switching-surge control, using pre-insertion resistors and shunt compensation, together with its effect on the voltage magnitude and time to crest value must be included in the analysis (Dahab 1991).

The use of the closed-form concept for electromagnetic transients in power networks resulting from sequential switching operations has been tried (Carsimamovic and Mahmuteehajic 1989). An efficient algorithm for transients in lines (Hamed and Esmail 1994) is modified to be suitable for the new problem of compensation.

Circuit Parameters

Consider a very small element dx of the line shown in Fig. 2(a) at a distance x measured from the receiving end. Then, z dx may be the series impedance of the studied length dx, and y dx is its shunt admittance. The voltage to neutral at the end of the element toward the load is V and at the generator side is V + dV. The rise in voltage over the elemental length of line in the direction of increasing x is dV (Hamed 1987). The elemental voltage and current through it can be expressed as

$$dV = I\ z\ dx$$

and

$$dI = V\ y\ dx \tag{1}$$

The real part of the propagation constant γ is called (Esmail 1992) the attenuation factor α, measured in nepers per unit length. The quadrature part of γ is the phase constant β, measured in radians per unit length. It can be expressed as $\gamma = \alpha + j\,\beta$.

In power-system work, characteristic impedance is sometimes considered as surge impedance. The later term is usually reserved for the special case of a lossless line. If a line is lossless, its resistance and conductance are zero so that the characteristic impedance might be $\sqrt{L/C}$. For high frequencies, or with surges due to lightning, losses are often neglected and the surge impedance becomes valid.

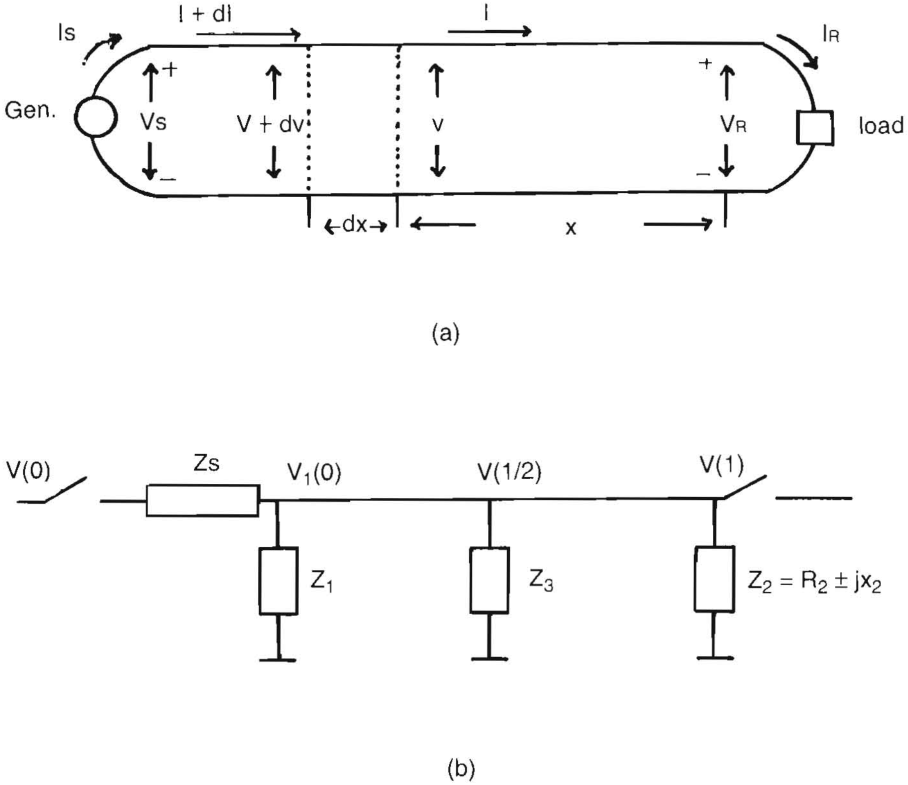


Fig. 2. The single line diagram of studied line.
(a) The distributed parameter characteristic.
(b) The compensated line.

Power-system engineers sometimes find it convenient (Esmail 1992) to express the power transmitted by a line in terms of per unit of surge impedance loading (SIL), as the ratio of the power transmitted to the surge impedance loading as $\mathrm{SIL} = |VL|^2 / (\sqrt{L/C})$.

Characteristic Impedance

Since the surge impedance Zc is sometimes used (Dmokhoviskaya 1972) as the characteristic impedance Zc, the deduced error should be justified. As the Laplace transform of percentage error $\varepsilon(s)$ is defined, the original time-domain function $\varepsilon(t)$

of this percentage error will be expressed according to Magnusson 1972 by:

$$\varepsilon(t) = (R/2L)\, e^{-RT/2L} \left(I_1(Rt/2L) + I_0(Rt/2L)\right) \qquad (2)$$

where I_1 and I_0 are the modified Bessel functions.

Using the convolution theorem with calculation intervals of T_0, the original of percentage error with respect to characteristic impedance can be written in the final mathematical form:

$$\varepsilon\left(\frac{t}{T_0}\right) = \frac{\varepsilon(0)}{T_0 F(0)} \cdot \frac{1}{F(0)} \sum_{m=0}^{t} \{\, \varepsilon(m).\, [\frac{t}{T_0} - \frac{t}{T_0} + \varepsilon(t/T_0 - m) - m]\} \qquad (3)$$

The percentage error due to consideration of surge impedance instead of characteristic impedance can be evaluated as in Fig. 3(a) for different values of attenuation factor. It is seen that the difference is minimum at small durations.

Figure (3) shows that the exact characteristic impedance must be considered for transient durations due to the rapid variation in the very small time intervals.

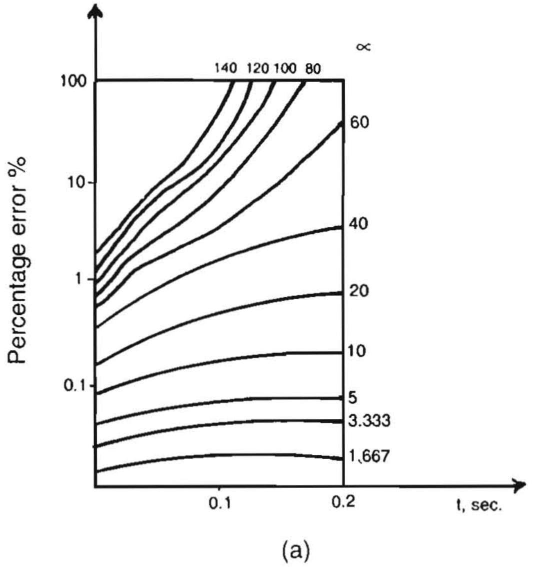
Propagation Constant

Since the main parameters of a transmission line are frequency dependent, their exact values should be considered when calculating the transients which may occur in a transmission line. The exponential function of propagation constant γ is considered. Then, according to basic parameters of Magnusson 1972, the scalar value of propagation constant can be derived in closed form as:

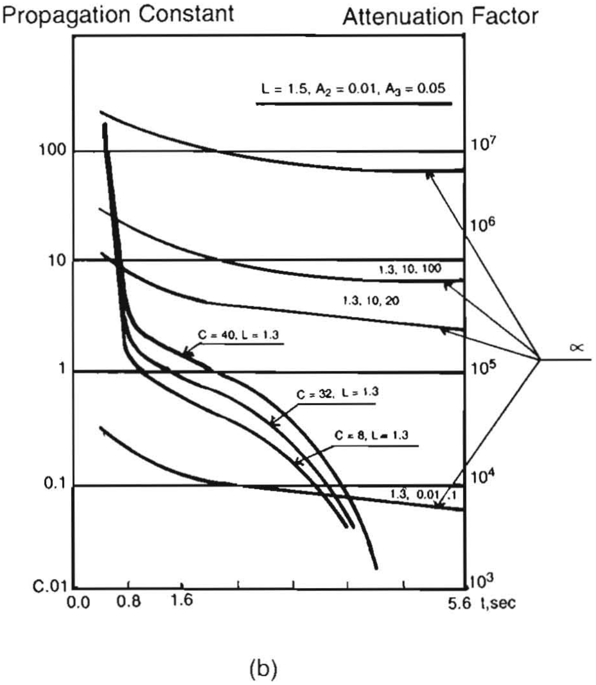
$$\gamma = \frac{L\, C\, e^{-\alpha t/2}\, I_0(\alpha\; t/2)}{e^{-\alpha t} \times 1} \qquad (4)$$

The calculated values are given in Fig. 3(b) for different parameters of the circuit L and C. The symbol α represents the attenuation factor which will now be studied.

The propagation constant is actually a complex factor. The value of γ given in Equ. (4) appears to be the scalar quantity of the vector of propagation constant. This equation is programmed and the results of calculations are given in Fig. 3(b). Its values are hardly decreased in the small intervals of times which represent the



(a) The attenuation coefficient.



(b) The propagation constant.

Fig. 3. The time-domain characteristics of fundamental parameters affecting transient performance.

transient conditions, especially in the electromagnetic transient period. This process is repeated for different values of circuit parameters. It should be noted that propagation constant depends more strongly on the attenuation factor α than on phase shift β.

Attenuation Factor

The attenuation of travelling waves along a transmission line is not constant with either time or distance. It is difficult to represent the attenuation of a voltage wave at the receiving and transmitting ends of a line by any simple superposition concept. Various techniques for simulating multi-phase attenuation and distortion have been given previously (Magnusson 1972). The positive wave should be attenuated faster than the negative wave. Clearly, the effect of corona on distortion and therefore on attenuation cannot be considered to be independent of the front duration (Mahmutchajic and Fischer 1989).

The attenuation factor may be mathematically deduced from the given expressions of Magnusson 1972 in the simple form:

$$\alpha = 1/LT_0\,(2\sqrt{t/\pi}.\, A_1 + t.A_2 + 1.33 + t.A_3\sqrt{t/\pi}) \qquad (5)$$

Where A_1, A_2 and A_3 are constants for the transmission line. They depend on the line geometry as given by Magnusson 1972.

The first term of Equation (5) decreases with distance and represents the attenuation, the second represents the time delay factor since it is a function of Laplace operators *i.e.* the velocity of wave propagation.

Study of the wave attenuation only is not sufficient to ascertain the overall shape of a propagated wave. It is very important to relate the wave velocities with the attenuation factor.

The attenuation factor plots in Fig. 3(b) take the form of exponential functions while the change of propagation constant is very high at short durations (up to 0.8 ms) before decreasing smoothly. Both attenuation factor and propagation constant are frequency dependent.

Wave Velocity

The other main factor is the propagation velocity. The difference between the velocities of wave modes may cause complicated propagation characteristics. The travelling time and attenuation of frequency components can be different and this modifies the shape of response functions (Morcos and Anis 1989). Attenuation and distortion of short-tail travelling waves at voltages below the corona limit have been obtained on some power lines.

The attenuation factors in first and second wave modes of the three Clarcke components for a single-circuit transposed transmission line are also frequency dependent (Hamed 1987).

Voltage and Current

Assume that each element of a phase wire is parallel to the Earth's surface and the height of the conductor is constant along the line. Also, neglect energy radiation from the conductors and assume that the Earth is homogeneous.

The voltage and current at a point x of a lossless line are given by

$$\left.\begin{aligned} [V(x)] &= [\cosh \gamma x]\ [V(0)] + [Zc \sinh \gamma x]\ [I(0)] \\ [I(x)] &= [\cosh \gamma x]\ [I(0)] - [\sinh \gamma x]\ [Zc]^{-1}\ [V(0)] \end{aligned}\right] \qquad (6)$$

For lossy transmission lines, Equations (6) become

$$\left.\begin{aligned} [V(x)] &= [\cosh \gamma(l-x)]\ [V(l)] + [Zc]\ [\sinh \gamma(l-x)]\ [I(l)] \\ [I(x)] &= [Zc)^{-1}\ [\sinh \gamma(l-x)]\ [V(l)] + [\cosh \gamma(l-x)]\ [I(l)] \end{aligned}\right] \qquad (7)$$

Sylvester's theorem (Hayashi 1955) appears to be important in the above analysis enabling the roots of matrix $[\gamma]^2$ to be determined as

$$\left.\begin{aligned} \lambda_1 &= \sqrt{\gamma_1 + 2\,\gamma_2} \\ \lambda_2 = \lambda_3 &= \sqrt{\gamma_1 - \gamma_2} \end{aligned}\right] \qquad (8)$$

Consequently, the matrix of propagation coefficient $[\gamma]$ can be reduced into only two terms and thus the exponentional value of γ (whether positive or negative) can be also deduced and formulated as

$$
\left.\begin{aligned}
e^{[\gamma]x} &= \frac{1}{3}\, e^{\lambda_1 x} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} + \frac{1}{3}\, e^{\lambda_2 x} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \\
e^{[\gamma]x} &= \frac{1}{3}\, e^{\lambda_1 x} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} + \frac{1}{3}\, e^{-\lambda_2 x} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}
\end{aligned}\right. \tag{9}
$$

This concept has not been published else-where so that its application is repeated for all terms of the Equation (7) and then its algorithm is programmed. For the compensated transmission lines of Fig. 2(b), the voltage at the receiving end may be accounted as:

$$V(l) = [Z_2]\ I(l) \tag{10}$$

The voltage at the midpoint of a line can then be derived as

$$
\left.\begin{aligned}
V(l/2) &= [\cosh \gamma l/2]\,[V(l)] + (Z_c)^{-1}\,[\sinh \gamma l/2]\,[Z_2]^{-1}\,[V(l)] \\
I(l/2) &= [Z_3]^{-1}\,[V(l/2)] + (Z_c)^{-1}\,[\sinh \gamma l2]\,[V(l)]
\end{aligned}\right] \tag{11}
$$

Introducing the series compensation Zs, the solution can be simplified as scalar formula in wave mode coordinates as:

$$
\frac{V(0)}{V_1(0)} = 1 + (Z/Z_1) + \frac{\dfrac{\sinh \gamma l}{Zc} + \dfrac{1 + \cosh \gamma l}{2\, Z_3}}{\cosh \gamma l + \dfrac{Zc \sinh \gamma l}{2\, Z_3}} \tag{12}
$$

The last two terms represent the voltage drop in the part of compensation at the sending end. This equation gives the facility for choosing the types of compensation either series, parallel, series and parallel, or finally without any compensation at all.

However, the present work is based on the transformation of equations in the time domain into the complex plane. This transformation reduces the differential equations of a line into algebraic form which can be readily solved. The closed-form solutions must then be returned to the time domain using the convolution integral (Hamed *et al.* 1989) as the inverse Laplace-transform process. So the voltage and current in mode coordinates are deduced in the time domain, and the program should transform them into phase coordinates again.

Compensation

Compensation means a modification for electrical characteristics of an electric circuit in order to increase its transmission capability (Abou El-Ela 1991). A compensation system ideally produces a substantially flat voltage profile, increasing the maximum transmissible power and meeting the reactive power requirements of a transmission system. Since the impedances of network components are predominantly reactive, the transmission of active power requires a difference in angular phase between voltages at both ends.

Shunt reactors are needed to compensate the effect of distributed line capacitance, particularly in order to limit voltage rise at either no load or light loading. The tend to increase the virtual surge impedance and reduce the virtual natural load. Shunt capacitors may be used to augment the natural capacitance of heavy loads. They generate a reactive power which tends to boost the voltage as well as to reduce the virtual surge impedance and to increase transmitted power.

Series capacitors are used for line-length compensation. Usually, a measure of surge-impedance compensation is necessary with series capacitors and this may be provided by an active compensator. Active compensators are usually shunt-connected devices which have the property of tending to maintain a substantially constant voltage at their terminals. Active compensators may be applied either for surge-impedance compensation or for compensation by sectionalizing.

This situation is most likely to occur when very long lines are being energized and it is probable that shunt reactor compensation would, in any case, be employed in such cases for other reasons. The effect of series capacitors on the maximum value of energisation overvoltage is small (Esmail *et al.* 1991). Study must start from the case of uncompensated lines in order to produce the reference result. This case will be defined for zero value ($X = 0$).

A typical 500 kV, 500 km transmission line is chosen for comparison. The results of the method used showed a good agreement with others (Dmokhoviskaya 1972, Hamed and Momtaz 1984, Papadopoulas *et al.* 1990).

Series resistance is mainly required in order to improve the performance of an electrical system in abnormal operation or under faulty conditions. For reactive compensation, this view will be changed due to the heavy reactive power generated in a power system. In other words, capacitive series compensation may be required to eliminate some of series inductive impedance of a line under steady-state operation. On the other hand, inductive series compensation modifies electrical characteristics of an electric system under short-circuit conditions. This last case is equivalent to the installation of resistive series compensators (Esmail *et al.* 1991).

The computer program is used to investigate a typical 500 kV, 500 km transmission line for 50 Hz supply. Fig. 4 presents the effect of series compensation on receiving-end voltages. Results show that the time constant of the applied waveform varies according to the rating of the series compensation. Also, the waveform is highly distorted with respect to the increase of series reactance X.

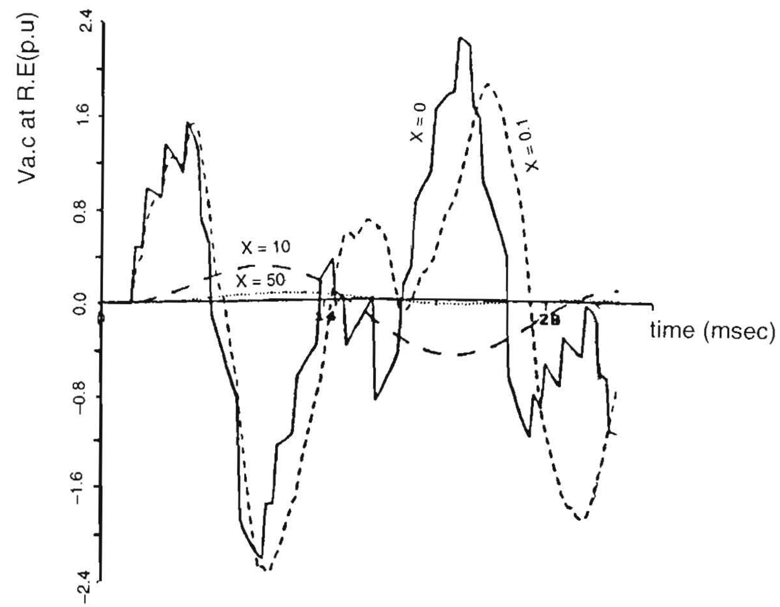


Fig. 4. The computed receiving-end voltage for a typical 500 kV, 500 km series-compensated line.

It is more difficult to obtain the overall characteristic for the case of an AC supply due to the variation of switching angle. Results demonstrate that for a certain switching angle (90°), the peak value of voltage deviates from $t = 0$ at $X = 0$ to $t = 9.66$ m.sec. at $X = 100\ \Omega$. The dependence of the front voltage on the series compensation is considered and the results of calculations prove that at low values of series compensation, the front voltage linearly increases up to 10 ms, then it becomes constant for any increase of series compensation (Esmail *et al.* 1991).

Usually, shunt compensation can be implemented in transmission lines in order to compensate the generated reactive power of transmission. First of all in transmission systems, shunt compensators are installed as fixed inductive or fixed capacitive devices or as a variable inductive capacitive device (Hamed *et al.* 1987). In Egypt, both fixed and variable inductive capacitive synchronous devices are installed at the 500 kV network.

In order to satisfactorily operate a long HV transmission line under steady-state conditions, it is necessary to compensate the charging reactive volt amperes produced by shunt reactors. At higher operating voltages above 400 kV, these reactors are often connected to the high-voltage line rather than to the transformer winding. Shunt reactors reduce energisation overvoltages if they are connected directly to the line. The reduction obtained depends upon the rating of shunt reactor as well as on its position in the system.

In general, a greater reduction might be expected when the reactor is connected at the receiving end. For weak sources (large inductance), pre-insertion resistors become increasingly effective in the reduction of energisation overvoltages as the natural frequency of the source and line approaches the power frequency (Hamed 1987).

Rate of Rise of Front Voltage (RRFV)

A new major factor is now presented to reflect the behaviour of insulation. This is the so-called "rate of rise of front voltage" for the wave propagated along the line differs some what from the factor "rate of rise of maximum voltage" which has been investigated earlier (Hamed and Esmail 1994). It is calculated for a typical 500 kV transmission line under different conditions of compensation. It has been concluded that the maximum front voltage decreases exponentially with respect to increase of the impedance of series compensations X (Esmail *et al.* 1991).

This means that at high values of series compensation, the insulation level becomes independent of the power of series compensation since the impedance of series compensation is greater than about 100 Ω. This may explain the necessity of installing series compensation in transmission lines. This indicated that series reactor (called the limiting short-circuit reactor), also decreases the transient voltage level.

More investigation is required to clarify the effect of series compensation on the behaviour of an UHV transmission line under transient conditions *(e.g.* a typical 750 kV 400 km can be tested for such a behaviour) (Hamed and Esmail 1994). For this purpose, the voltage at receiving-end is calculated as shown in Fig. 5. It is seen that the peak value occurs at the time point number of 42 when as the time of each point interval is 0.00023 sec. This case is taken as a reference for the subsequent evaluation of the rate of rise of front voltage for wave propagation along the line under different conditions.

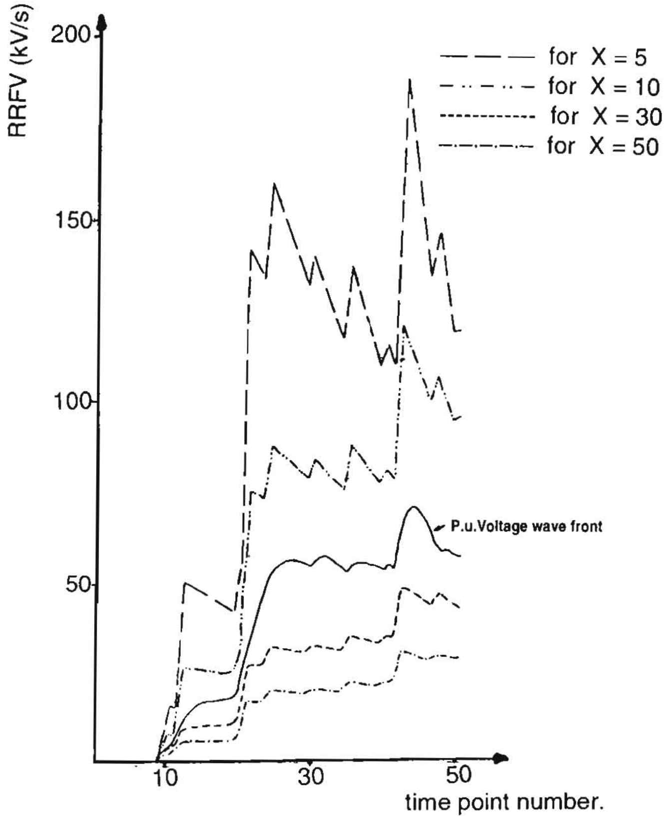


Fig. 5. The calculated rate of rise of front voltage (RRFV) for a typical 750 kV, 400 km line with different ratings of series compensations.

The effect of introducing series compensation on 750 kV level is studied. Referring to Fig. 5, it is concluded that the presence of series inductive compensation decreases the peak value itself. However, it can be seen that the maximum RRFV also decreases with increasing the value of series compensation. Also, Fig.5 shows that the distortion of wave front increases with larger values of series compensation X since the wave rise becomes less with the increase value of X.

It should be mentioned that there are two peaks for the values of RRFV at time point numbers 21 and 42. The first time point of 21 has the maximum rate of rise while the time point number 42 has about 66.28% of this maximum value of RRFV at time point 21. This may be exactly calculated as it appears as 85, 73.11, 55.32 and 51.67% for the series compensation of X as 5, 10, 30 and 50 ohms, respectively.

Whatever the effect of series compensation on the performance of the front wave of a transient voltage at the receiving end of a UHV transmission line, it will be necessary to study the dependence of this variation on the line length. This necessitates computation of the transient voltage at the receiving end of the proposed 750 kV typical line for different values of length in the range from 100 km to 700 km. The results of the calculation are presented in Fig. 6.

Fig. 6 shows that the maximum RRFV decreases with line length at a constant value of series compensation. So, an envelope is drawn in order to clarify the above conclusion. It can be concluded that the recommended length for a 750 kV lines from the transient point of view should be in the range of 300 $\rightarrow$ 500 km since the RRFV is minimum in this region of line lengths.

The calculated values of RRFV for 500 kV lines with shunt compensation are drawn in Fig. 7. It is seen that the effect of shunt compensation is similar to that of series compensation at sending end while its effect at receiving end differs. The parallel inductor has practically no effect on the rate of rise of front voltage. The results confirm the accuracy of the method study since they reflect a small insulation level for the equivalent condition of a short-circuited line at the receiving end. This condition is equivalent to zero value of G. By increasing this value, the operation of a line approaches the case of a highly loaded (over loaded) transmission line. Since the effect of series compensation is clear at both ends, the distribution of the proposed factor (rate of rise of front voltage) is determined along the studied line as shown in Fig. 7. It has been concluded that the voltage level of a transmission line can be gradually levelled along the line length (Esmail 1992).

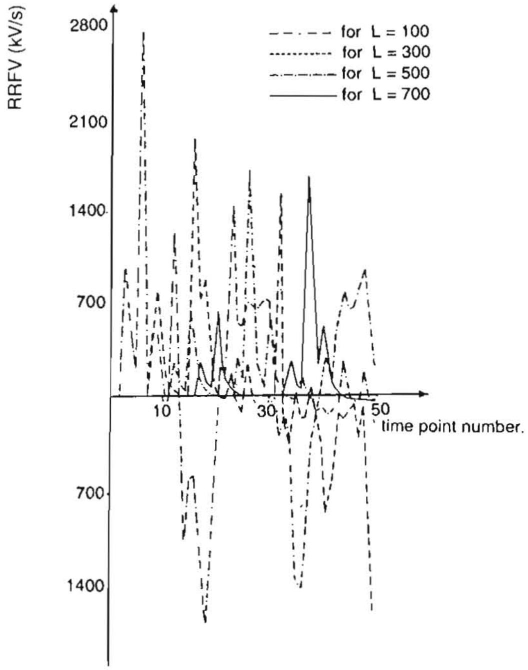


Fig. 6. The calculated rate of rise of front voltage (RRFV) for a typical 750 kVseries-compensated line with different lengths.

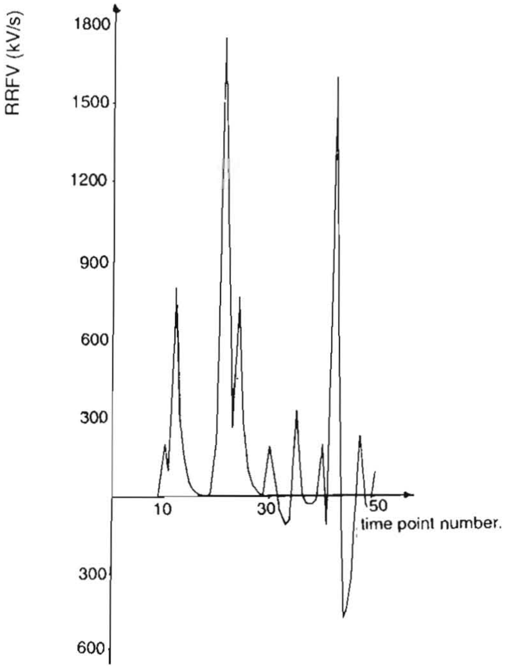


Fig. 7. The calculated rate of rise of front voltage (RRFV) for a typical 500 kV, shunt-compensated line.

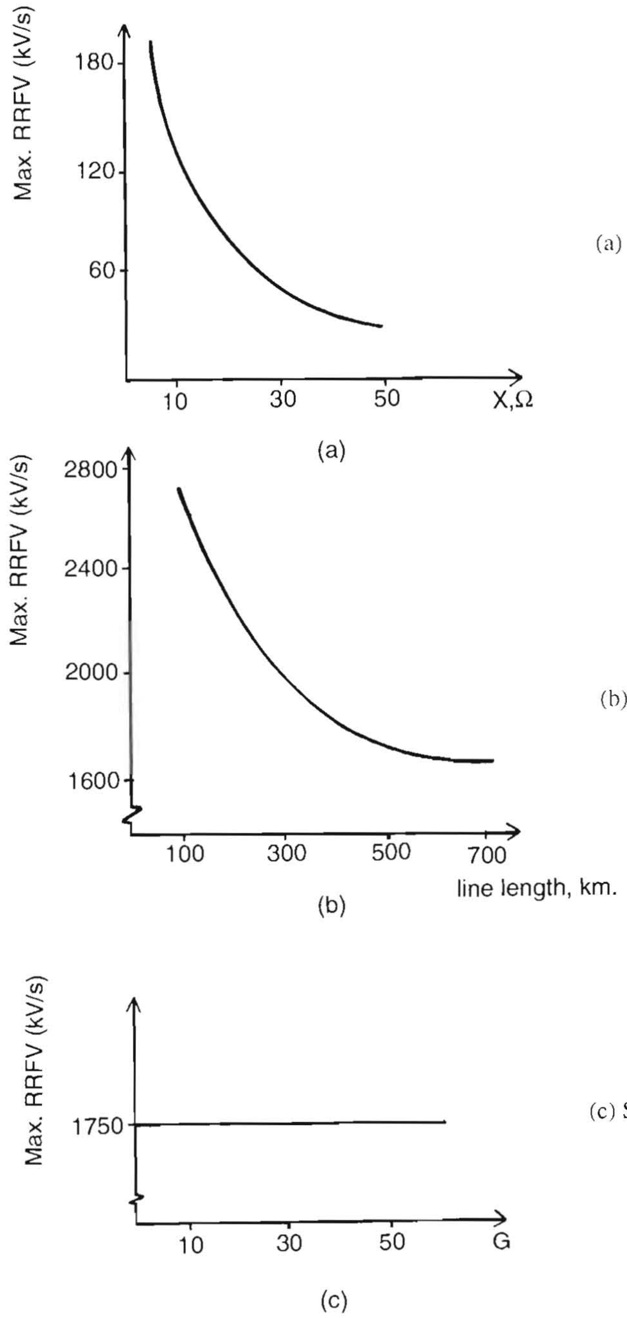
For a typical 750 kV 400 km transmission line, a sinusoidal waveform has been considered in order to derive the deformation factor on such a wave along the line. The deduced first half wave along the line is studied. The results introduce a new factor which may be called the "deformation rate for the proposed rate of rise of maximum voltage". It should be noted that the rate of rise of maximum voltage given by Esmail (1992) differs from the proposed RRFV given in Fig. 8. The RRFV values are calculated for each time interval while the rate of rise of maximum voltage has been evaluated for the time difference from zero voltage up to a maximum. It has been shown (Esmail 1992) that the deformation of a waveform is highly presented at the first quarter of the line length, then it decreases smoothly and exponentially.

It must be noted that the value of shunt compensation G of Fig. 8 has no effect on the RRFV at all even with change in the line length. It is concluded that either series or shunt compensation or even both can control the maximum internal transients in long transmission lines. This shows that the RRFV does not depend on shunt compensation while the maximum magnitude of transient voltage decreases with increase in the rating of shunt reactors at receiving end. This conclusion coincides with that of Esmail *et al.* 1994.

Dependence of the Maximum Value of RRFV

The RRFV appears to be an important factor for the study of wave fronts from the viewpoint of not only front distortion but also in terms of the peak value of wave transient voltage. It becomes ever more important as the values of RRFV become very high. However, the dependence of RRFV on both series and shunt compensation (X and G respectively) is investigated. For shunt compensation, the variation of RRFV relates only to the switching angle as well as the section of waves at which they are to be calculated.

Therefore, the study of maximum RRFV values becomes very necessary in order to determine the effective rise on the wave front. This is more important for UHV transmission lines where the voltage rise produces a high stress on line insulations. For this purpose, the maximum values of RRFV become interesting and so their dependence on the studied parameters should be presented and analyzed as shown in Fig. 8. The dependence of the maximum value of RRFV on both the variation of series compensation X (as shown in Fig. 8(a)) and line lengths (as given in Fig. 8(b)) are shown. Also, the change of the shunt compensation at the receiving end of a line is illustrated in Fig. 8(c).



(a) compensation X rating.

(b) line length.

(c) Shunt compensation (G)

Fig. 8. The calculated maximum rate of rise of front voltage (RRFV) in kV/s for a typical 750 kV, 400 km series-compensated line as a function of variation in (a, b and c).

From the relationships given in Fig. 8, it is seen that the maximum value of RRFV in kV/s depends exponentially on the length for series-compensated transmission lines. On the other hand, it increases very fast with decrease in the rating X of series compensation banks. Consequently, the installation of series compensator banks at the sending end of a line not only limits the abnormal currents but also reduces the transient voltages in the line under switching conditions.

It should be mentioned that the effect of shunt compensation on the maximum value of RRFV is constant and this maximum value of RRFV does not depend on the rating of the shunt compensators, as shown in Fig. 8(c).

As investigated above, it is concluded that the voltage at sending end of a transmission line does not depend on large banks of shunt compensation. The effect of charging capacitance will be reduced due to passing the AC current through shunt capacitors. A little increase in voltage at the sending end may appear according to the presence of shunt reactors at the receiving end. This increase should be reduced quickly prior to the steady-state condition.

Conclusions

1. Exact values of the main parameters of a line should be introduced in the calculation of electromagnetic transients in transmission systems.
2. The proposed computer program, which can be used on personal computers even without hard disk, is recommended to be used for the calculations of internal and external transients in both transmission and distribution networks.
3. The limiting short-circuit reactor decreases the insulation level of the line.
4. The maximum rate of rise of front voltage exponentially decreased with line length.
5. Shunt reactors are highly effective in lowering the levels of switching transients and are very necessary for EHV and UHV transmission systems.
6. The effect of shunt reactors is constant for all lengths of transmission lines.
7. The factor "rate of rise of front voltage" is recommended for study of transients in transmission systems.
8. More investigation is required to clarify the effect of series compensation on the behaviour of an UHV transmission line under transient conditions.

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تأثير التعويض المتوالي والمتوازي على الجهود الداخلية العابرة في خطوط النقل الهوائية

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يقدم البحث دراسة تفصيلية لمعاملات الخط الرئيسية والتي تؤثر بصورة فعالة في ظاهرة الجهود الداخلية الانتقالية في خطوط النقل الكهربية . كما انه قام البحث بتوضيح العلاقة الزمنية لتأثير هذه المعاملات وشملت كلا من الازمنة الملائمة للفجائيات في خطوط الكهرباء كما تضمنت تأثيرها المباشر على التشغيل العادي لهذه الخطوط . يعرض البحث بالتحليل الرياضي قيم الجهود الداخلية العابرة في شكلها العام باستخدام المصفوفات وينتهي باستنباط برنامج يصلح تشغيله على الحاسبات الآلية الشخصية . تمت مناقشة مستوى العزل للخطوط تحت الدراسة ووضع العلاقات المميزة لهذا العزل بالنسبة للابعاد الهندسية لاسلاك الاطوار الثلاثة بالنسبة لمستوى الأرض . يدرس البحث موضوع تعويض القدرة غير الظاهرية في خطوط القوى الكهربية مشتملا كلا من التعويض المتتالي والتعويض المتوازي مع تضمينها في برنامج الحاسب الالكتروني المعروض والذي يعتبر بسيطا سواء في الاستخدام مع تقصير وقت الحساب مما يوفر عملية الحساب اقتصاديا . وفي حالة التعويض تمت دراسة التعويض السعوي والتأثيري مع وضع الخلاصة لبعض الحالات المدروسة وعرض حالات معينة تستدعي الدراسة والبحث خلال العمل البحثي . يقترح البحث معامل جديد باسم معدل زيادة الموجة الامامية للجهد وهي أكثر العوامل المؤثرة في مستوى عزل خطوط نقل القدرة الكهربية . وبالتالي تمت

عملية حساب الجهود العابرة عند نهاية خط قياسي جهد ٧٥٠ك ف لطول ٤٠٠ كم ومنها تم حساب هذا المعامل المقترح ومن ثم استنتجت القيمة القصوى لهذا المعامل وإيضاح مدى تأثيرها سواء في حالة التعويض المتتالي أو في حالة التعويض المتوازي .

كلمات فاتحة : الجهود العابرة - خطوط النقل الكهربي - التعويض - انتشار الموجات - تشوه الموجات - القدرة غير الظاهرية .