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THE TRANSMISSION OF BULK POWER OVER LONG DISTANCES

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Circular, plate, radial and coaxial arrangements for phases of double circuit transmission lines are proposed. Power transmission over long distances depends on the mutual effect between each two respective phases. A theoretical analysis for voltage, power and current along such lines is presented. The general constants for each configuration are evaluated, as well as the maximum power limit for long distance double circuit transmission lines. Different voltage levels of 500 and 1000 kV are considered for a length of 1000 km. An external impedance is suggested to be connected at various points of coaxial arrangement with separate phases. The capacitive effect for such an external impedance is studied.

INTRODUCTION

UHV transmission up to 1600 kV appears to offer particular advantage principally to those countries where large generation sites are located far from load centers. Such sites will undoubtedly utilize coal, hydro or nuclear fuels.

A very important factor in the future of UHV, which has not been presented in the past, will be the need to move large blocks of energy over long distances because of changes in the world's fuel situation. An advantage of UHV transmission stems from the fact that, by its use, it may be possible to utilize existing concentrated energy sources, or even to concentrate energy sources in a few areas particularly suitable for safety or environmental reasons. This would avoid spreading generation plants all over the territory.[1]

The use of UHV may be more influenced by special requirements (environmental, nuisance) than by purely economic choice so that the future of UHV will depend on the development of proper technical solutions to match these requirements. Although it has been concluded that UHV DC transmission represents an alternative for very long distances (1000–1500 km), the AC transmission appears as the main tool for such a transmission.[1]

LINE CONNECTION

As blocks of power are generated at a long distance from load centers, a new idea for power transmission will be necessary. This has been tried previously [2]. The single line diagram for the proposed connection is given in Fig. 1. The phases of the first circuit A, B and C are connected only to the generating end while phases of the second circuit a, b and c are connected to the load at the receiving end. For such circuits the mutual effect

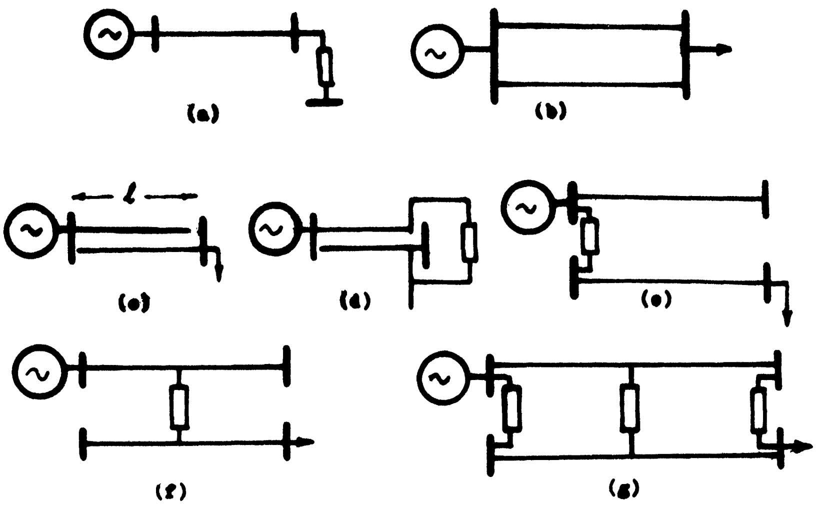


FIGURE 1 The single line diagrams for different connections of circuits of the proposed transmission line: (a) ordinary single circuit line, (b) ordinary double circuit line, (c)–(g) the proposed type of lines

between the group of phases (A-a), (B-b) and (C-c) is not the same. Also, the power limit for natural transmitted power through such a line may be varied according to configurations of phases (Fig. 2).

The effect of mutual capacitance C_{nm} and mutual inductance M_{nm} between phases n and m is accounted. For accurate representation, the equivalent circuit for the shown line should be given for an incremental distance dx (see Fig. 3). This representation leads to an exact analysis for steady state performance.

GENERAL CONSTANTS

The telegraphic equations of a line for voltage V(x) and current I(x) at a distance x as a function of main parameters (resistance R, inductance L, conductance G and capacitance C) may be expressed in the form:

$$-dV_n(x)/dx = (R_{nn} + jwL_{nn})\, I_n(x) + \sum_{\substack{m=1\\ m\neq n}}^{6} jwM_{nm}\, I_m(x)$$

$$-dI_n(x)/dx = -\left(G_{nn} + jwC_{nn} + \sum_{m=1}^{6} (G_{nm} + jwC_{nm})\right)\cdot \qquad (1)$$

$$V_n(x) + \sum_{\substack{m=1\\ m\neq n}}^{6} (G_{nm} + jwC_{nm})\, V_m(x)$$

where w is the angular frequency.

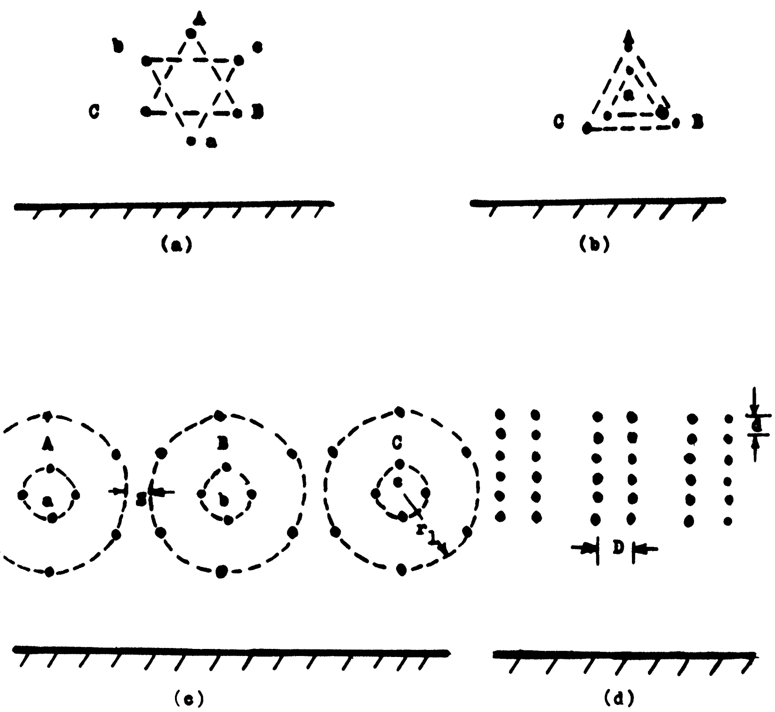


FIGURE 2 Different configurations for conductors of phases of the proposed line: (a) circular, (b) radial, (c) coaxial, (d) plate type.

The general expression for voltage and current at a point x of a line may be formulated as:[6]

$$\begin{aligned} V_{A,a}(x) &= A_{1,2} \cosh a_1x + B_{1,2} \sinh a_1x + \\ &\quad C_{1,2} \cosh a_2x + D_{1,2} \sinh a_2x \\ I_{A,a}(x) &= A_{3,4} \cosh a_1x + B_{3,4} \sinh a_1x + \\ &\quad C_{3,4} \cosh a_2x + D_{3,4} \sinh a_2x \end{aligned} \tag{2}$$

The integration constants $A_{1,2,3,4}$, $B_{1,2,3,4}$, $C_{1,2,3,4}$ and $D_{1,2,3,4}$ can be determined in terms of current and voltage at the generating end using the terminal conditions.[2] The main parameters such as admittance Y, impedance Z, and, propagation coefficient a can be estimated.[2] If the mutual effect between the two circuits is disappeared, the deduced equations will be the same as an ordinary line.[3] This can be considered as a check for the obtained expressions.

As the general constants depend on the main parameters of a line, they must be investigated for different configurations of phases. For circular arrangement of conductors (Fig. 2a) as well as for radial configuration (Fig. 2b), the general constants are estimated. Although mathematical expressions for constants A_0 and D_0 are not identical, calculations prove that their values are the same. Also, the angle of constants A_0 and D_0 is close to

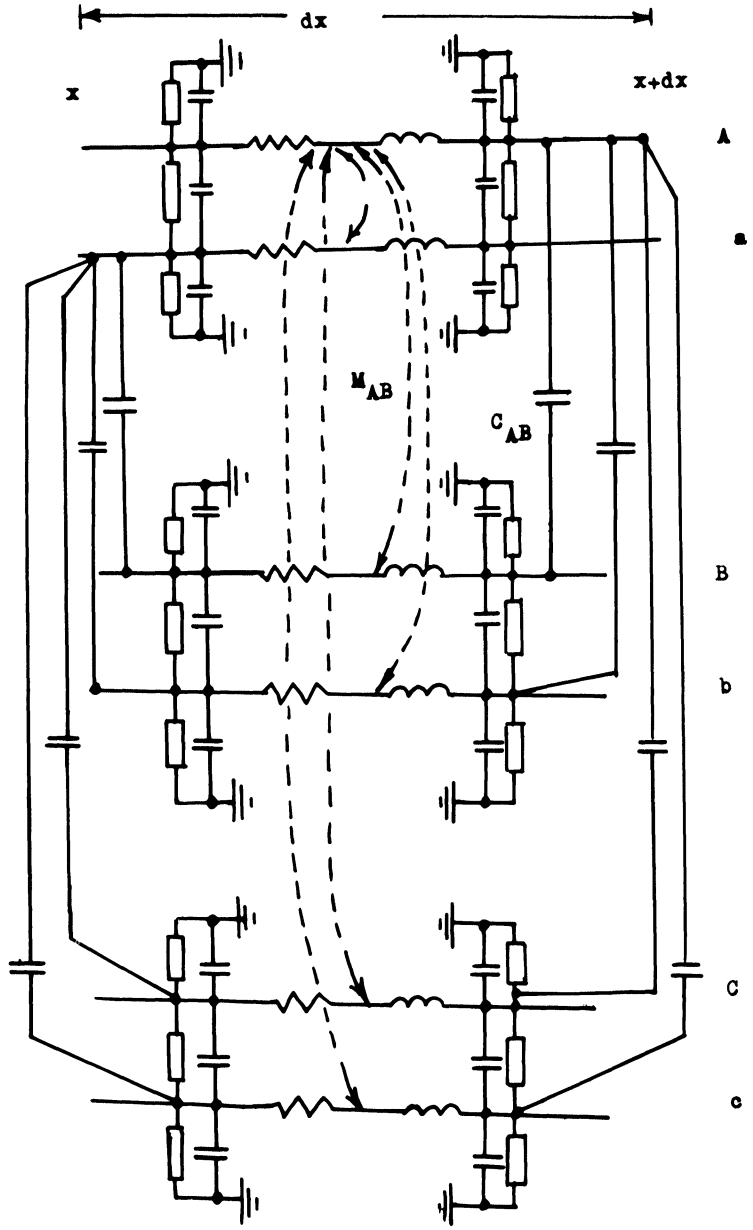


FIGURE 3 Equivalent circuit for a section dx of a line.

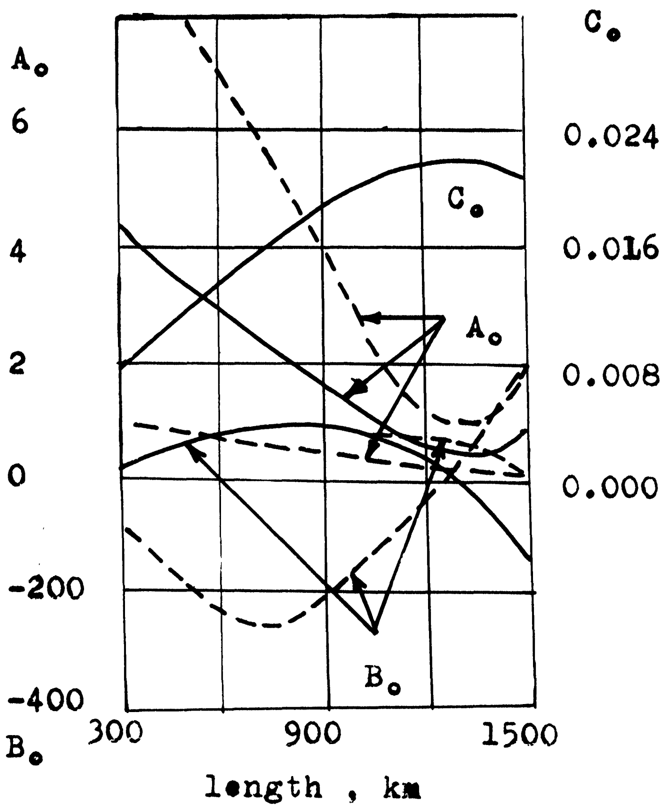


FIGURE 4 The calculated general constants of the proposed lines.

that of ordinary line.[2] The general constant B_0 in resistive coordinates is obtained as shown in Fig. 4.

The magnitude of constant A_0 for radial arrangement as well as for ordinary double circuit transmission line is decreased by increasing the line length up to 1200 km, after which its value is increased (see Fig. 4). This means that the mutual reactance between conductors is capacitive with a minimum magnitude of constant B_0 while shunt admittance is capacitive up to 1500 km according to the results of calculations. Thus, radial geometry of conductors appears to be better than circular configuration.

POWER LIMIT

There are various methods to increase the power limit through long lines; by rising the transmission voltage or by loading the line with reactors at suitable intervals. Accordingly, the power limit of such a line as a whole would be equal to that of the section that has minimum power limit. On the other hand, the power limit can be increased by introducing a capacitance in the circuit to compensate the inductive effect of a line. In order to check the suitability of a radial arrangement of conductors, the maximum transmitted power should be compared for both configurations.[4,5]

The estimated maximum received power as a function of line length ensures that the radial arrangement is still the best and the circular configuration should be excluded from next investigation.[5] Then, the magnitude of constant C_0 for a radial geometry is evaluated as plotted in Fig. 4 while its angle is very close to 90° at all lengths. The maximum values of its magnitude are at lengths of 1000–1400 km.

STEADY STATE OPERATION

As steady state performance for radial arrangement is required, voltage and current distribution along the 1000 km line at an open-circuit condition must be studied. This process may appear at normal operations of a network. The results of calculations prove that the angle of current I_A does not vary along the line and its value is constant at 79°, while for voltage it is about $-12°$. Applying a unity voltage at the generating end, the computed distributions of voltage and current are evaluated.[3]

Finally, the proposed radial arrangement may be the best for the transmission of large blocks of power only over long distances.

The spacing between conductors for the arrangement in Fig. 2a appears to be large owing to the placing of all phases on the same circle and the required spacing for UHV transmission will be impracticable. Improving the radial arrangement with multi-radial conductors, a modified configuration can be suggested as shown in Fig. 2c. The inner phase will have q_2 conductors per phase and outer phases have q_1. It must be mentioned that the deduced equations for voltage and current can be simplified if the mutual effect between both circuits is neglected.

EXTERNAL COUPLING

It should be noted that spacing is generally imposed by some requirements so that the main practical control of electric field may be achieved by conductor height above ground.[6]

The reactive power of a line can be compensated by either system impedance or power of loads. Shunt and series capacitors, shunt reactors and synchronous condensers have been used for a long time while static VAR systems have been applied in the last decade.[7] However, this compensation can be realized by the proposed arrangement of conductors.

On the other hand, if a line operates satisfactorily in the steady state, the transient behaviour would be questionable and, by rapid control of voltage, the transient characteristics can be greatly improved.[4] As it was concluded above that a forcing impedance must be connected at receiving end to increase the power limit, this case should be investigated now.[8]

(a) Single Place Coupling

To improve the steady state characteristics of the proposed type of transmission systems, it is desired to insert a forcing impedance X between conductors of the same group of

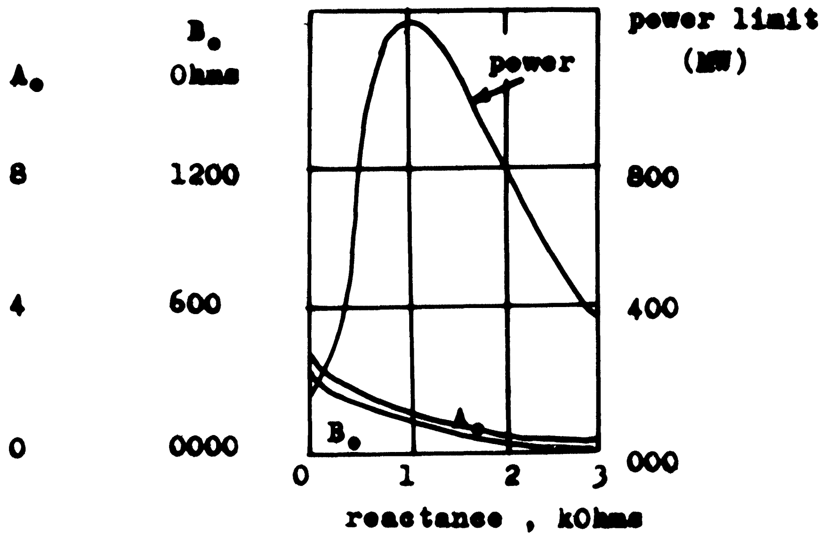


FIGURE 5 The effect of capacitive reactance on power limit and on general constants of a line with separate coaxial phases (connection of Fig. 2c) for the single line of Fig. 1d.

phases at only the receiving end as shown in Fig. 1d. These conductors must not be connected to any external impedance at the sending end.

For the proposed coaxial lines with a forcing impedance, the general constants A_0 and B_0 are computed for different values of a capacitive reactance as plotted in Fig. 4. When the values of capacitive forcing reactance are increased by compensating the line series impedance, the magnitude of constants A_0 and B_0 will be decreased. If an inductive forcing reactance is introduced, the value of the general constant A_0 rises to its maximum at 500 ohms, and then decreases again to the value of the same line but without a forcing impedance.

For equal terminal voltages, the computed maximum received power is plotted in Fig. 5. The power limit is increased up to its maximum at 1 kohm.

This may be explained by the rise in the potential difference between adjacent conductors A and a to increase the mutual effect between them. After a certain point, the line should be overcompensated and the power transfer from a conductor to the other will be reduced.

As the capacitive reactance becomes high, the mutual effect between conductors appears and the power limit approaches that value of a line but without forcing impedance.

It is also seen that the maximum power limit for a 500 kV, 1000 km transmission line occurs when a 1 kohm forcing capacitive reactance is connected. However, the practical possibility of this type of line depends on the condition for maximum power limit. The results of calculations show that this power limit is 1200 MW and the transfered power from one conductor to another in each group of phases will be increased by about 33% of that line but without a forcing impedance.

For a 500 kV, 1000 km transmission line with different connections as given in Fig. 1, the voltage distribution along both load and generator circuits is computed. The load

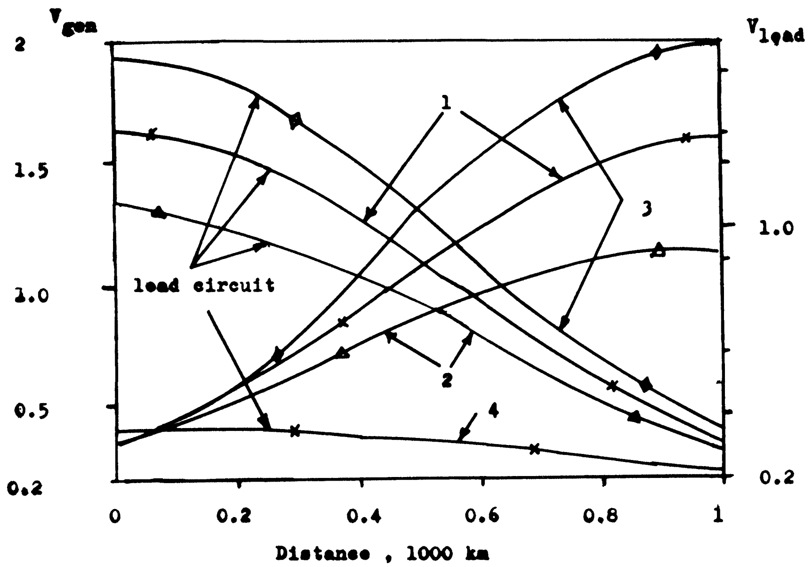


FIGURE 6 The voltage distribution along the proposed 500 kV, 1000 km transmission line: (1) reactor at receiving end (2) reactor at middle point (3) without reactors as Fig. 1c (4) ordinary double circuit line.

impedance of 50 Ohms is considered. The results of calculations are plotted in Fig. 6. From this figure it is seen that the installation of a reactor at the middle point of a line modifies the shape of voltage distribution along it. This proves that the reactive connection between circuits may increase or decrease the voltage level of the suggested line under the steady state operations. Then, current as well as power will be also varied.

(b) Multi Place Coupling

It is seen that the voltage of 500 kV appears to be at a low level relative to the transmission of electric power over long distances such as 1000 km and a higher voltage level should be applied. Hence, a voltage level of 1000 kV may be required for the study of the proposed concept of power transmission [9].

Since there are no published fundamental parameters (resistance, inductance and capacitance) of overhead transmission lines for such a voltage level, the extrapolation technique is used to deduce the approximate values of the necessary parameters of a line. The results of these calculations are listed in Table I.

As the electrical performance depends on the connection of external reactances between both circuits of a 1000 kV, 1000 km transmission line, modified connections for the external inductive reactances are given in Fig. 7. Then, each external reactance will be equal to ten times the self inductance of the line phase. In this case voltage, current and power distributions along both load and generator circuits of a line are evaluated. The results of computations are plotted in Fig. 8.

Alternatively, the external inductances of Fig. 7 are replaced by capacitances as shown

TABLE I
The parameters of EHV and UHV transmission lines

Voltage (kV)	Resistance (Ohm)	Inductance (Ohm)	Admittance (μ Mho)
66	0.1380	0.414	2.75
220	0.0800	0.392	2.85
500	0.0217	0.295	3.96
1000	0.0050	0.110	5.50

in Fig. 9. The external capacitance C_{ex} is equal to ten times the self capacitance for the line phases. The evaluated voltage, current, and power are then recomputed for the connections of external capacitances. The results of calculations are drawn in Fig. 10.

DISCUSSION

It is clear that the presence of a reactor at the middle point of a line has more effect on the voltage distribution than the installation of a reactor at the receiving end (Fig. 6). This leads us to the importance of reactor connections at different points along the line

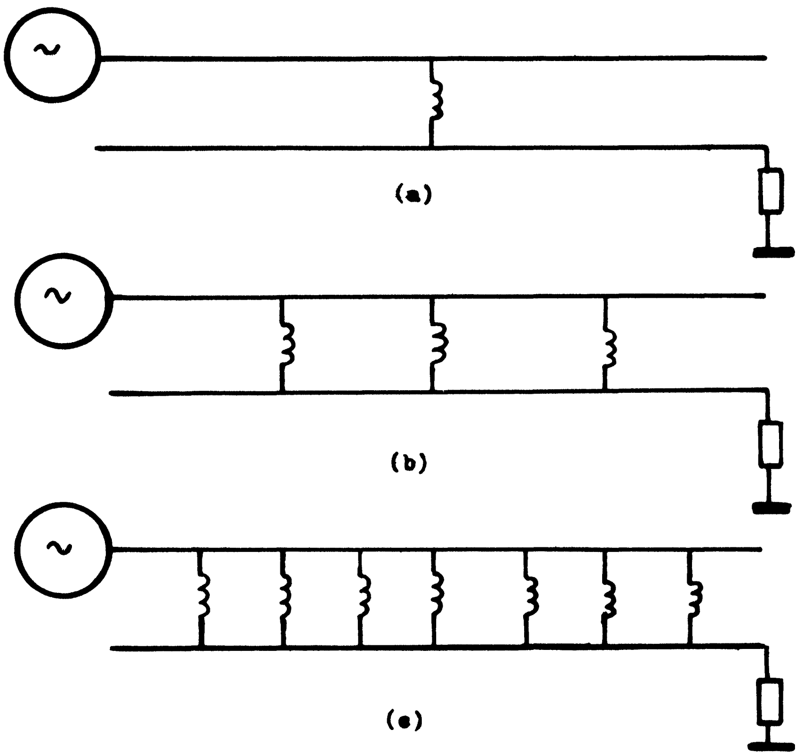


FIGURE 7 The single line diagrams with external reactors at various points of the proposed line.

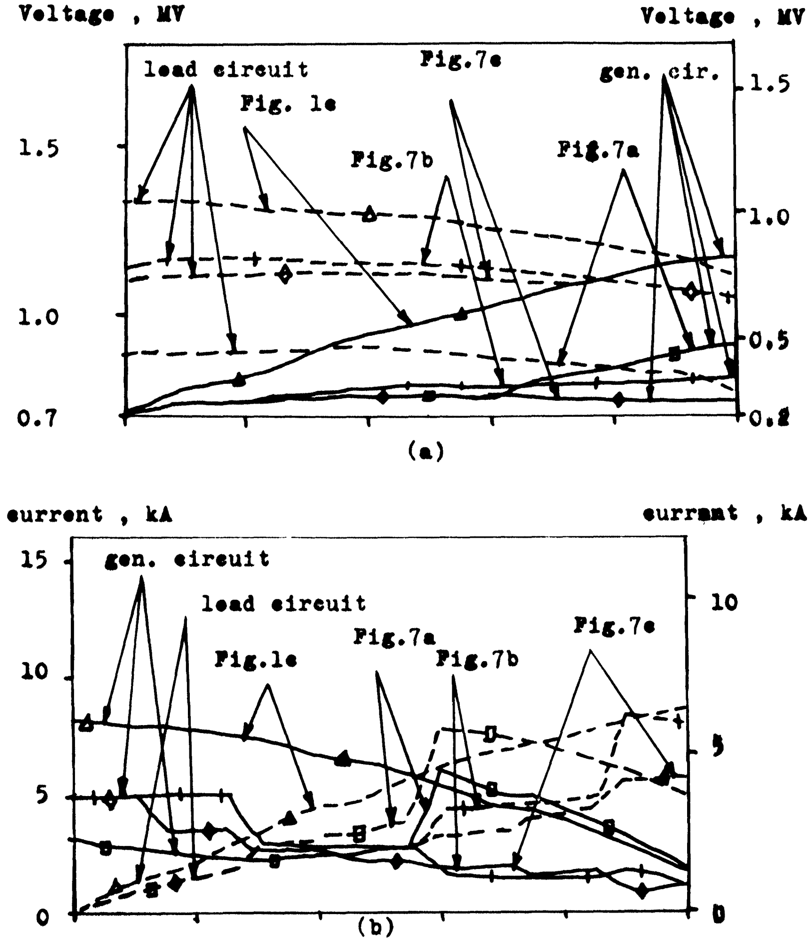


FIGURE 8 The computed performance for the proposed line connections.

(Fig. 7). The exact middle point reactor (Fig. 7a) has the best performance for voltage distribution. This means that there is no need to install any other reactors rather than at the middle point.[8]

Although the current at load impedance appears to be less than others, its value is close to the connection of single line diagram of Fig. 7c. This proves that the received power may be lower but this connection is still the best for the performance of a line (Fig. 8). Thus, the connection of a reactor at the only the middle point between both generator and load circuits of the proposed line is recommended to reduce the voltage level under operation.[9]

Accordingly, the effect of capacitance installation should be also investigated. The voltage along the line is decreased due to the presence of a capacitance at the middle point (Fig. 9a), but its value is higher than the condition of the middle reactor. As a

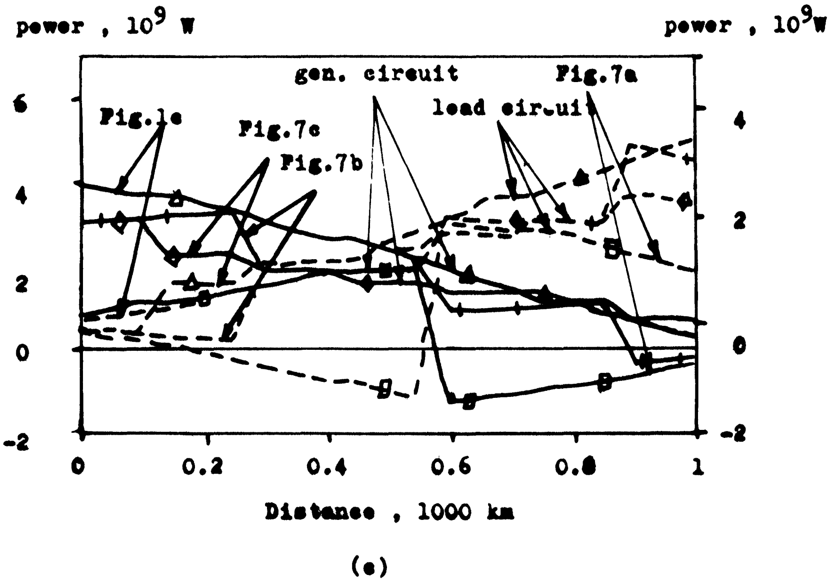


FIGURE 8C

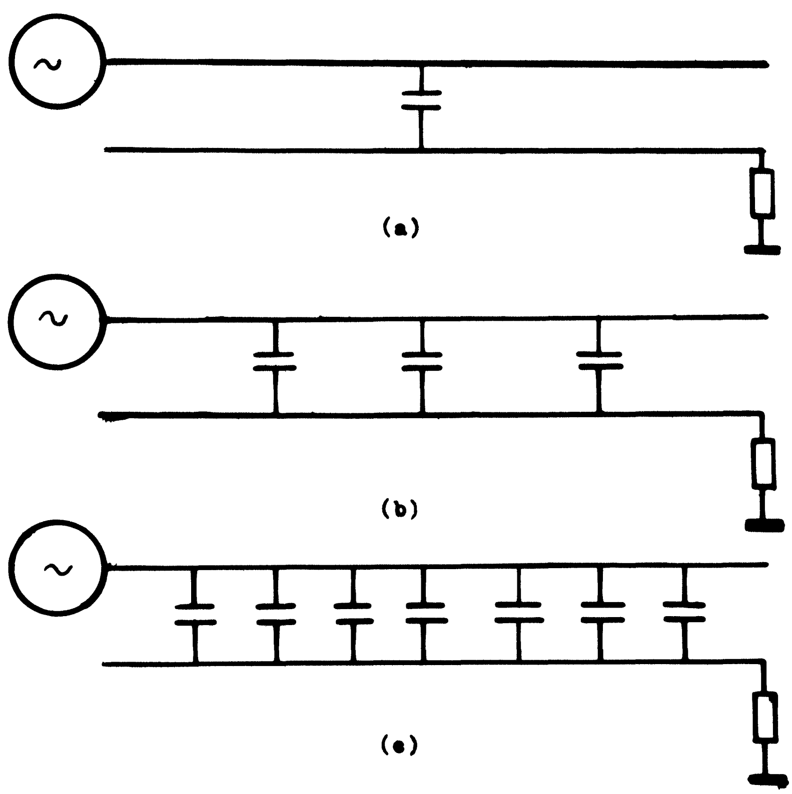


FIGURE 9 The single line diagrams for a line with external capacitance at different points.

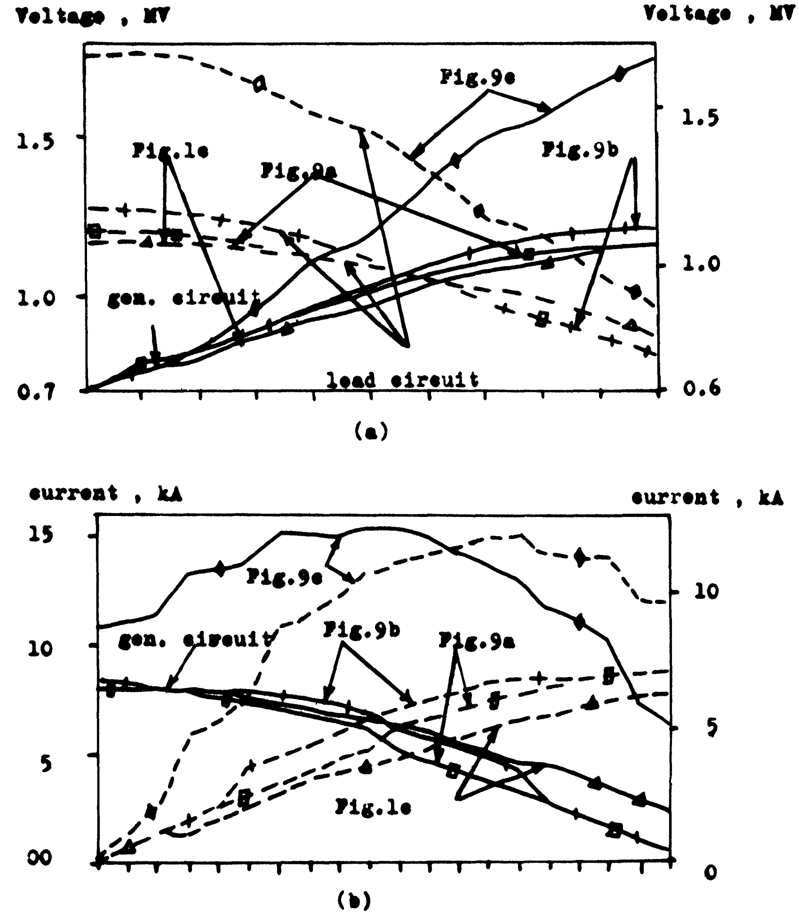
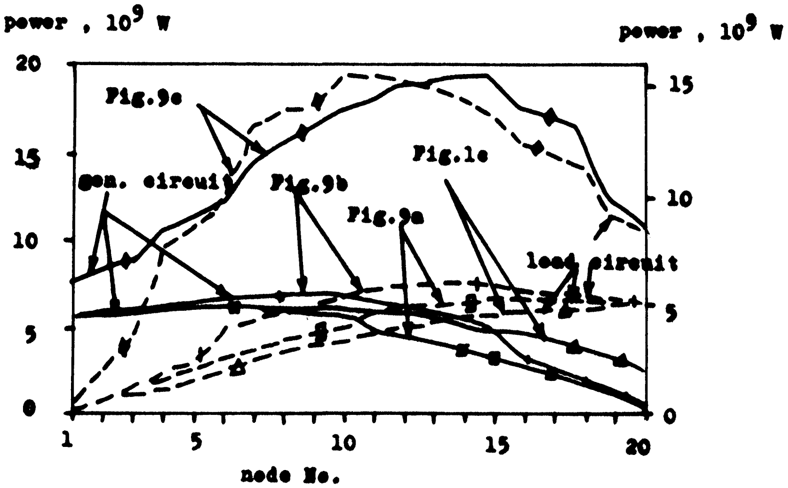


FIGURE 10 The deduced characteristics for the proposed connections of a line.

result, the case of middle capacitance should be removed from the next investigation. The received power is greater for the connection of Fig. 9c. This means that the effect of terminal external capacitances is higher for power transmission. So, an external capacitance at the receiving end must be installed between the two circuits (Fig. 5). Thus, the proposed type of transmission lines with single line diagram of Fig. 1g is recommended for the application.

CONCLUSIONS

The coaxial arrangement with separate phases of double circuit lines may be recommended for long power transmission.



(e)

The presence of an external reactor at the middle point between the two circuits of a line modifies the voltage distribution along it under steady state operation. The effect of an external capacitance at the receiving end increases the power limit.

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