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ECONOMIC CONSIDERATIONS GOVERNING THE CHOICE OF VOLTAGE FOR POWER SUPPLY SYSTEMS

by F. Wienken, H. Dorsch and W. Bückner

NOTE: This text is subject to editorial revision.

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/1. Introduction

1. Introduction

The rapid progress being made in electrification in all parts of the world is accompanied by the requirement that greater quantities of power be transmitted, a condition which in turn necessitates the raising of the transmission voltages. It is these developments which today make vital the selection of voltages affording both economical and technical advantages. Since the cost of power must be kept as low as possible and since consideration must be given to the relatively high capital outlay, which is not always easy to cover, special attention must be paid to the economical design of the electrical plant. An important point here is the selection of suitable voltages and steps.

The selection of the voltages for a power distribution system is influenced by a number of factors, such as the power to be transmitted, the load development, consideration of existing voltages, evaluation of the losses, standardization etc. For this reason there are practically no standard solutions to the multitude of problems, and the most that can be done is to provide general directives for the selection of the voltages as obtained from economic studies and experience gained with existing systems.

If the distribution system is not very extensive, has to supply only small loads and is fed from a nearby source of power, such as Diesel power stations or small hydroelectric power stations, possibly one voltage alone will suffice, i.e., the voltage taken by the consumer. The conditions change immediately if the sources of power are located a long way from the centre of gravity of the load, if the power supply is obtained from other systems or if the power to be transmitted and the physical extent of the system under consideration exceed certain limits. This makes additionally necessary a system having a higher voltage. If the physical extent and load demand in a system grow appreciably, a further higher voltage may be necessary in order, for instance, to transmit the large amounts of power from the power stations, whose location is fixed, to the centre of gravity of the load. By employing very high voltages it is also possible to more advantageously interconnect large power supply systems with their different sources of energy, i.e., to obtain economical interconnected operation.

/Technical considerations

Technical considerations may also make it desirable to employ high voltages. As is known, the short-circuit capacities also increase with the amount of power to be transmitted. Very high short-circuit capacities and their effects can be economically controlled by the employment of high voltages.

Depending on the particular problems to be solved, a power supply system may thus incorporate 1, 2, or more voltage levels which are necessary to satisfy the load requirements and obtain economical inter-connected system operation. In numerous countries these various voltage levels have been clearly defined. Table 1 gives a survey of the various voltage levels and their range of application. In the following, a distinction will be made between "low voltage, medium voltage, high voltage and extra high voltage". Their relevant ranges are shown in table 1.

In the planning of every new scheme it is essential to check which voltages will provide the most economical solution, taking into account all influencing factors, and also in the case of extension to existing systems to carry out an investigation to determine whether the existing voltages will be economically and technically satisfactory over a long term or whether economical considerations make it imperative that existing voltages be changed completely or partly, immediately or subsequently. A further consideration is to which voltages preference should be given. At very high voltages it is also necessary to take into consideration climatic conditions and dimensioning of the insulation.

2. Low voltage

The selection of the low-voltage value is determined by the standards and safety regulations applying in the various countries as well as by economical considerations. The voltages usually employed in public supply systems are up to about 450 V and in industrial plants up to 600 V. However, we will not here go into further details concerning the selection of suitable voltages for the low-voltage supply. Within certain limits the voltages at this level should be considered as being given. The main subject dealt with in the following will be the voltages at higher levels.

/3. Medium

3. Medium voltage

On account of the restricted distance over which power can be transmitted, low-voltage systems are generally supplied from a medium-voltage system through transformer stations. In medium-voltage systems practically all voltages are encountered between 3 an 35 kV. Simple studies show that economical reasons obviate the employment of voltages below 10 kV and it can be also assumed that in the relatively wide range remaining the economical medium voltage may vary widely in accordance with the power demands and the geographical conditions.

In order to provide criteria for the most economical medium voltage, a survey is first given of the costs as a function of the voltage of the equipment required for the construction of a medium-voltage system. In each case the costs at 10 kV are assumed to be 100 per cent. The equipment in this case involves overhead lines, cables, transformers, transformer stations and switching stations.

Figure I.1 shows the cost curve for three-phase overhead lines for the two cross-sections 35 and 70 mm^2 of steel-cored aluminium conductors.[1/] Between 10 and 35 kV the costs rise continuously with a relatively flat slope, those for the smaller cross-section rising somewhat higher than those for the larger one.

Figure I.2 shows the cost curve three-phase cables for the two cross-sections 50 and 120 mm^2 of copper.[1/] The rate of rise is appreciably more than in the case of overhead lines. Added to this is a sudden and appreciable increase in costs on the changeover from belted to S.L. cables.

Figure I.3 shows the cost curve for transformers with ratings of 50 and 200 kVA.[1/] The increase in costs here is greater between 20 and 30 kV than between 10 and 20 kV.

Figure I.4 is the cost curve for complete transformer stations similar to figure I.3.

Figure I.5 the cost curve for switching stations shows a higher

1/ The object of the various cross-sections and power ratings is to illustrate clearly the influence which they exercise.

/increase for

increase for plants having a low short-circuit capacity (200 MVA[2]), whereas the increase for plants with a high short-circuit capacity is relatively small.

From figure I. 1 to 5 it can be seen that there is no appreciable saving in the costs in the voltage range from 3 to 10 kV as compared with 10 kV. Decisive in this voltage range is the need for larger conductor cross-sections at certain power values, a condition which generally makes distribution systems at voltages less than 10 kV uneconomical.

A general survey of the percentage cost of the individual items of equipment in medium-voltage systems is shown in figure I.6. On the left is the subdivision of the costs for a rural medium-voltage system constructed with overhead lines, and on the right that for an urban system constructed with cables.

Since the loads and load groups in rural medium-voltage systems are generally far apart, the lines are very long. Thus, the costs for rural systems are mainly determined by the costs of the overhead lines. Since the costs of overhead lines increase only slightly with the voltage, while the transmission capacity and the transmission distance increase greatly, and since in addition to this, the selection of a higher voltage and smaller conductor cross-sections brings about an appreciable reduction in the costs, the most economical voltage for rural medium-voltage systems will generally be in the region of the higher values (see the example on page 7).

In an urban cable network the conditions are different. The lengths of the cables are much shorter as compared with the overhead lines in rural systems, whereas the number of transformer stations and the station ratings are much higher. By reason of this, the costs of the transformer stations play a more important role as the power involved becomes higher. Since the costs of cables increase more with the voltage than do the costs of overhead lines, the most economical medium voltage will not have a tendency towards such high values as in the case of rural overhead lines. Experience has shown that the economical medium voltage in cabled distribution systems can cover the relatively wide range from 10 to 20 kV. It will tend more

2/ The object of the various cross-sections and power ratings is to illustrate clearly the influence which they exercise.

/towards 10

towards 10 kV where, for instance, the power to be transmitted does not exceed certain limits, and where no great influence is exercised by long lengths of cables made necessary by a unilateral position of the feeding junctions and the bridging of areas with few or no loads, e.g., green belts, railway installations, and also where the number of large industrial loads, which require special switching stations for the transfer point, is large. Where large amounts of power and long transmission distances are involved, the economical medium voltage approaches the higher value of 20 kV. The employment of medium voltages lower than 10 kV can be considered as being economical only if the areas to be supplied are very limited or systems are involved which supply a large number of high-voltage motors (industrial systems).

On the basis of this knowledge it was recommended at the IEC conference at Stockholm in 1958 that in future no voltages below 10 kV be employed for distribution in public power supply sustems.

The following economical and technical considerations lend support to the employment of higher medium voltages.

(a) Higher transmission capacity of the lines

Figure II shows the economical power values for various conductor cross-sections at transmission voltages of 10, 20 and 30 kV. In some cases the magnitude of the power difference between the overhead lines and the cables is determined by the different materials selected, such as steel-cored aluminium conductors for overhead lines and copper conductors for cables. It is clear that raising the operating voltage increases the transmission capacity of overhead lines and cables appreciably more than does the increasing of the conductor cross-sections at the same voltage.

(b) Smaller voltage difference in the lines and higher permissible transmission distances with the same percentage voltage difference

As a supplement to figure II, figure III shows the range in km of medium-voltage lines and cables with a given voltage difference. (5 per cent for cables; 8 per cent for overhead lines) and with transmission of the economical power value. The range in km of the transmission systems increases almost linearly with the voltage. With a given voltage difference, greater

/ranges than

ranges than those indicated in figure III can be obtained only if the power to be transmitted is reduced, a condition which is no longer compatible with economical loading of the lines.

(c) Transformer stations with high rating and low specific costs

Since the economical size of medium-voltage load areas increases with the voltage, the transformer stations feeding into medium-voltage systems can be built for higher outputs thereby reducing the specific costs. Added to this, is the fact that the costs of the superimposed high-voltage system are likewise reduced.

(d) Lower transmission losses

For the same conductor cross-section, the system losses decrease with the square of the increasing voltage. Even if the conductor section is reduced inversely proportional to the voltage, the system losses still decrease linearly with the increasing voltage.

(e) Reduction of the line costs by selecting a smaller cross-section

If correspondingly smaller conductor cross-sections are selected as the medium voltage increases, the capital costs of the overhead lines and cables decrease. Of course consideration must be given to the fact that a lower limit is created by the thermal short-circuit rating.

(f) Lower short-circuit stresses at the same short-circuit capacities

As the voltage increases the short-circuit current is reduced, i.e., on the development of a short circuit the resulting stresses are smaller thereby limiting the extent of any possible damage.

(g) Reduction of the number of outgoing circuits from the transformer stations

The number of outgoing overhead lines and cables from a transformer station is limited. In the case of unduly low medium-voltages, large outputs result in accumulations of outgoing cables, a condition which not only creates technical difficulties but may also involve additional costs.

The economic advantages of high medium voltages are particularly prominent where the power capacity of the higher voltage can be fully utilized. With the aid of two examples, one of an urban cable system and

/the other

the other of a rural overhead line I will try to illustrate the cost relationships for systems having medium voltages between 10 and 30 kV supplying power to areas which differ in size.

1st example (figure IV)

Medium-voltage cable system: load density 2 MVA/km^2; average size of the system substations 315 KVA, 75 per cent loading; cable cross-section at 10 kV: 3 x 120 mm^2 Cu; at 20 kV: 3 x 70 mm^2 Cu; at 30 kV: 3 x 50 mm^2 Cu. Loss costs (includes price of energy kWh and power kW) 60 US $ per kW per year; radius of the load area: alternately 1 km, 2 km and 3 km corresponding to a power in the area of 7.9 MVA; 31.4 MVA; 70.6 MVA.

The specific costs determined for the system contain both the capital costs and the capitalized costs of the losses from the transformer station to the secondary side of the system substations, referred to the power distributed. The costs were fixed at 10 kV and R = 1 km being equal to 100 per cent. As could be expected, the cost curves show that the value of the economical voltage increases with the size of the load area. On account of the costs for the system substations, however, distribution voltages above 20 kV are no longer economical.

2nd example (figure V)

Medium-voltage overhead line system; load density 10 kVA/km^2; average size of the system substations 100 kVA (polemounting stations); 60 per cent loading Overhead line cross-section at 10 kV; 3 x 70 mm^2 steel-cored aluminium; at 20 kV: 3 x 50 mm^2 steel-cored aluminium; at 30 kV: 3 x 35 mm^2 steel-cored aluminium. Loss costs (includes the price of energy and power) 60 US $ per kW per year; radius of the load area: alternately 10, 20 and 30 km corresponding to a power in the area of 3.14 MVA; 12.56 MVA; 28.2 MVA.

The specific system costs were fixed at 20 kV and R = 10 km being equal to 100 per cent. For the three selected radii the cost curves are at a minimum between 20 and 30 kV, this minimum being displaced towards higher voltages as the size of the load area increases. In general it can be said from this that such rural systems should be operated at high voltages round about 20 kV, and in exceptional cases even up to 30 kV. Voltages below 15 kV should be avoided since these are uneconomical.

/4. Superimposing of

4. Superimposing of high voltage

In the higher power ranges a high-voltage system is superimposed on the medium-voltage system in order to transmit the energy economically from the power stations or from the interconnected network to the centres of gravity of the load, and from there to feed it to the medium-voltage system via transformer stations. The ratio of the superimposed voltage to that of the medium-voltage system should be at least 3:1 and at the most 10:1, as has been shown by economy studies.

In special cases the magnitude of the voltages to be superimposed is determined primarily by the power to be transmitted and the length of the transmission lines. Figure VI shows an example of the transmission costs for the voltages 30, 60 and 110 kV as a function of the power to be transmitted, three transmission distances being selected in each case as the parameter. A comparison is made of the costs of single-circuit lines (figure VIa) and cables (figure VIb) including the associated switching stations, the annual loss costs being capitalized with a factor of 10.

The cost curves show that from certain values of power upwards it is more expedient to select the next higher standard voltage, this depending on the distance involved. Allowance must be made here for the fact that the value given does not include all the associated switching stations in the system (switchgear units for transformers, coupling units) and the connected transformers, all of which increase the costs when a higher voltage is selected. When making the decision as to the most suitable voltage, therefore, the costs of these switching stations and transformers must be added proportionately to the costs of the lines. This results in the intersecting points of the curves for the different voltages being displaced to the right, i.e., to slightly higher power values. From figure VI it can be seen that the employment of higher voltages in rural overhead-line systems which have to transmit power over long distances is more economical than is the case with urban cable systems having short transmission distances, even at appreciably lower power ratings.

/The costs

The costs of the equipment increase more with higher voltages in the high-voltage range than is the case in the medium-voltage range, with the exception of overhead lines (figure VII). A particularly striking point here is the pronounced increase in the costs of the switching stations at higher voltages, whereas the increase in the costs of the overhead lines is relatively small. From this it can be seen that in extensive rural high-voltage systems, in which the overhead lines represent the greater part of the total costs, the transmission capacity of the system can be increased relatively cheaply by selecting higher voltages. This measure is of course expedient only if the capacity of the system is likely to be utilized in the foreseeable future.

In urban high-voltage cable systems the capital costs rise sharply with the voltage selected owing to the numbers of switching stations and quantities of cables required. The selection of the economical voltage is here even more important than in the case of overhead lines since the curve for the costs of the system, which is dependent on the voltage, is not flat but shows a pronounced minimum. The selection of the voltage in an urban system may also be influenced to some extent by the voltage of the infeeding interconnected system or by the transmission voltage of the power stations located in the vicinity. In many cases economical advantages can be gained by matching this supply voltage with that of the urban system since this obviates the need for transformers.

5. Considerations governing the stepping of voltage in distribution systems

The step between the medium voltage and the high voltage is governed by several factors. These include the development of the load with respect to time; the density of the load and its physical distribution; the voltage in the interconnected system; standardization of the voltage.

The higher the rate of load growth in a load area, the greater should be the difference in the two voltages since it can be expected that the superimposed high-voltage system will be economically loaded in the foreseeable future so that the capital outlay will pay for itself. An important point here is the rate of interest on the capital invested. Whether

/the required

the required capital is easy or difficult to procure is a further point to be considered.

Where the rate of development in the load is low, the ratio of 1:3 can be taken as a criterion for a suitable step from the medium to the high voltage. With normal growth in load this ratio rises to about 1:5. Only if the growth in load is above average and there are other reasons in its favour, should the step in the voltage be increased to about 1:10.

A further decisive factor is the load density and its distribution in the load area. The load density in a load area is not constant but may vary within wide limits. Thus, for instance, the centre of a large city has a load density of 20 MVA/km^2 in contrast to the value of only 0.01 MVA/km^2 of the rural outskirts included in the same load area. Whereas in the centre of the city the concentration of power would make the highest possible voltage step economical, e.g., 110/10 kV (132/13.2 kV) this might be uneconomical for the rural outskirts with a low load density. In these areas it would be expedient to employ an intermediate voltage with a ratio to the medium voltage of 3:1 to 5:1. With this intermediate voltage it would then be possible to supply the outskirts economically over a long period until the load has grown sufficiently to permit the intermediate voltage to be replaced by the high voltage in the city.

The step in the voltage can also be influenced by the voltage of the interconnected system. Either the voltage in the city and rural areas required for distribution must be matched with that of the interconnected system (to save further transformation), or if this is uneconomical owing to the loads being too low, an intermediate voltage must be selected which has a ratio suitable for both the medium voltage and the interconnected system voltage. In the latter case it might be possible later, when the loads increase, to partly or completely eliminate the intermediate voltage in order to obviate double transformation.

In the selection and stepping of the voltage consideration must be given to the existing standard voltages, which are unfortunately not uniform in all countries. The adaptation of the system voltages to the standard values not only simplifies the stocking of spares for the supply

/undertaking but

undertaking but also makes it possible for the electrical manufacturers to produce electrical equipment more rationally and thus more cheaply.

By the adaptation to the standard values, the selection of the voltage step in the system is simplified in that the number of alternative voltages to be studied with regard to their economy is reduced.

In practical application a multitude of voltage steps has been introduced. From the preceding studies it would, however, seem expedient to employ voltage stepping only within the following limits.

150 to 220 kV/60 to 70 kV/10 to 20 kV

110 to 150 kV/30 to 70 kV/10 to 20 kV

110 to 150 kV/10 to 20 (30) kV

6. Selection of the voltage for long transmission lines

(a) Technical considerations

An initial criterion for the selection of the operating voltage of high-voltage lines covering transmission distances of several hundred kilometres can be obtained from the so-called natural power of an overhead line. The natural power P_{nat} is determined by the surge impedance of the line Z and the operating voltage U_b:

$$P_{nat} = U_b^2/Z$$

The surge impedance of overhead lines is relatively little dependent on the geometrical dimensions of the lines and in the case of single-conductor lines is Z 370 to 400 ohms. The surge impedances of bundle-conductor lines are lower. The natural power of bundle-conductor lines is thus higher and, for instance, in the case of lines with two-conductor bundles is 30 to 40 per cent higher than with single-conductor lines.

Listed in table 2 are guidance values for the surge, impedances of single-conductor and bundle-conductor lines, these being based in each case on the required minimum conductor diameters. These minimum diameters are determined by the permissible electrical gradients at the surface with respect to the limiting of high-frequency interference and corona losses.

/In the

In the light of experience gained in Germany and also in accordance with investigations carried out a mean gradient at the surface (effective value) of 15 to 16 kV/cm can be considered as permissible.

Figure VIII shows the natural powers of single-circuit and double-circuit lines as a function of the voltage, the maximum permissible voltages U_m laid down by the IEC being specially marked. A value of $U_b = 0.95\ U_m$ has been assumed for the operating voltage.

For a 245-kV transmission line (U_b = 233 kV) we obtain for instance for a single line with one conductor per phase a natural power of 140 MW, and for a double line with two-conductor bundles a value of about 400 MW.

In the case of transmission distances in the range of over 500 km the transmission power is smaller than the natural power, unless additional measures are taken (e.g. series capacitors), to ensure the stability of the line. For shorter transmission distances in the range 100 to 200 km however higher transmission powers can be considered. In the case of very short lines, the transmission power is limited by the permissible thermal capacity.

(b) Economic considerations

Magnitude of the voltage

The selection of the economical operating voltage is dependent on the power to be transmitted and the transmission distance involved. In Fig. 9 are shown as a preliminary guide the voltages which can be considered, these being given as a function of the stated characteristic values. Thus, for example, the economical voltage for a line transmitting a power of 30 MW over a distance of 100 km is approximately U_m = 123 kV.

Shown in figure X are the annual transmission costs for the voltages U_m = 123, 245 and 420 kV as a function of the transmission power per system and of the transmission distance. The costs include also those for the transformer stations. The calculation has been based on an annual number of operating hours of 4 500 at a load factor of $m = 0.51$. A value of z = 10 per cent has been calculated for the annual rate of interest, depreciation and maintenance. The technical characteristic and the related costs of the lines under consideration are shown in table 3.

/From the

From the curves shown in figure X it can be seen, for instance, that the economical voltage for transmission powers of 100 MW per system is 245 kV. This applies for transmission distances from 50 to 400 km. For transmission distances from 400 to 600 MW per system the economical voltage is 420 kV.

Cross section of the conductors

For a given transmission power and the required transmission voltage consideration must also be given in the dimensioning of conductor cross-section to the economical current density. In figure XI, for instance, the economical current density for 245-kV steel-cored aluminium lines is given as a function of the load factor and the cost of energy, this being at a capital service of z = 12 per cent. It can be seen from this that the economical current density varies only within a relatively narrow range. At a load factor of m = 0.5 the economical current density at the usual prices of energy varies between 0.8 and 1.0 A/mm^2. For bundle-conductor lines and double-circuit lines the values obtained are approximately the same.

Taking the transmission current as a basis it is possible to approximate the economical cross-section as a function of the load factor. This must be designed to suit the permissible field strengths (conductor diameter, single conductor or multi-conductor bundle). Here, however, only the transmission costs of the line are to be considered. In actual transmission problems the final dimensioning must be checked in detail in regard to its economy for every case.

Dimensioning of the insulation

The costs of the equipment required in high-voltage transmission systems (transformers, high-voltage equipment, switching stations) are dependent on the required insulation level, i.e., on the required insulation capacity for impulse voltages and a.c. voltages (test voltages).

The basis for rational dimensioning and utilization of the insulation is the voltage stresses arising during operation. In overhead-line systems particular attention must be paid to voltage surges produced by atmospheric effects which can be effectively limited by installing surge arresters. The

/protective level

protective level ensured by the employment of surge arresters represents the basis for economical dimensioning of the insulation.

The protective level in systems having effective earthing of the neutral is lower than that in systems with arc suppression because on the development of earth faults the voltage to earth at operating frequency is smaller, thus permitting the use of surge arresters with a lower rated voltage, so-called 80 per cent arresters. Building up on the lower protection level of these arresters it is today international practice to reduce the insulation for systems having effective earthing of the neutral with high insulation ratings. This in turn reduces the requirements with regard to the impulse and a.c. voltage tests on the equipment thereby lowering the costs of the equipment.

Table 4 shows the values now recommended by the IEC on which the dimensioning of the insulation is to be based. A remarkable fact is that these IEC values have been recognized internationally and that many national rules and specifications have been brought into line with these values. It would be desirable and advantageous if these values could be adopted in countries which to date have no such directives and specifications since uniformity and limitation to a few insulation ratings would add much to the economy of power supply.

Table 4 shows the required impulse withstand voltage for the standardized full wave and also for the a.c. test voltage. Shown in the last column are the required minimum clearances in air which must be maintained in the construction of the plant. For an impulse level of 550 kV for the insulation class 123 f, for instance, a minimum clearance of 1 150 mm is required, whereas with reduced insulation in the insulation class 123 r only 920 mm is required. The building requirements for a 123-kV indoor station are for instance 20 to 25 per cent smaller if it is designed for an insulation level of 450 kV instead of for 550 kV. The building costs alone decrease in the corresponding ratio.

The ever increasing improvements made in surge arresters and the many years of satisfactory operating experience gained in numerous countries have resulted in an international trend towards reduction of the insulation

/level for

level for high-voltage transmission lines. Thus, today, for instance, in 245-kV systems in the USA having effective earthing of the neutral. some of the transformers are designed for a full-wave level of 750 kV, whereas the value required by the IEC is 900 kV.

A special problem is the economical and operationally reliable dimensioning of the insulation of outdoor stations and overhead lines where adverse climatic conditions are encountered, such as heavy industrial contamination, salt deposits in coastal area, etc.

In the case of all insulators whose surfaces are exposed to the effects of the atmosphere, the insulation capacity is reduced, in some cases appreciably, by fog, dew and conductive contamination layers. Particularly seriously affected by this is the insulation capacity with voltages at operating frequency. With voltage surges the influence is relatively limited. The a.c. test voltage under wet conditions which is still widely used for the selection of the outdoor insulation provides no indication as to the capacity of the insulation in a contaminated condition. Thus the employment of insulators able to withstand high a.c. test voltages represents no economical solution to the problem.

Recent findings, substantiated by experimental investigations and operating experience, have shown that it is possible by suitable surface design of the insulators (e.g. number and shape of the sheds) to appreciably improve the insulation capacity without making the length greater. In particularly difficult cases regular cleaning of the insulators (spraying while alive) has proved to be an economical solution. For some years now silicone greasing has been successfully employed.

<u>Design of the overhead line</u>

After the magnitude of the operating voltage, the conductor cross-sections, the required insulation and the route of the line have been selected a decision must be made as to the design of the supports for the line. Associated with this are investigations into the type of the tower, the foundation, the span, the conductor tension and the type of conductor. These are necessary in order to arrive at an economically and technically advantageous solution. Shown in figure XII are the

/subdivided costs

subdivided costs of high-voltage overhead lines from which can be seen how large is the percentage of the total costs required for towers and foundations (approximately 40 per cent). Thus, optimized design of these parts of the line has the same importance as the correct dimensioning of the electrically stressed parts of the line such as conductors and insulators.

The design of the towers determines not only the costs of the towers themselves but also to a great extent those of the foundations. In economical studies and in decisions as to the selection of the tower design this must always be taken into account. Particularly where the soil conditions are adverse is it possible for the foundation costs to assume a high proportion of the total costs. The use of towers with only three main members in place of four frequently results in appreciable savings in the foundations but not, however, in the towers themselves. For some time now tubular steel filled with centrifugally-cast concrete has been successfully used for the highly stressed main member in addition to angle iron. Recent developments have also been directed towards using for towers steel with a higher breaking strength than that used previously, the object of this being to save material and reduce the tower weight.

The fixing of the optimum span is primarily dependent on the magnitude of the voltage. Figure XIII shows that there is for every line an optimum span with which the total expenditure for towers, foundations, insulators, fittings, earthing systems, real estate and damage to ground is at a minimum. As the voltages increase so does the optimum span. This is also the case with poor soil conditions. Also important is the fixing of the conductor tension since this likewise influences the cost of the line. The magnitude of the conductor tension is dependent upon the operating voltage and must be determined from case to case.

7. Making allowance for existing plant in future extensions of the system

Our previous studies have been confined essentially to the determination of the economical voltages and voltage steps in new schemes. In many cases, however, existing power supply systems have to be extended. As a rule,

/the equipment

the equipment incorporated in these systems represents a considerable capital outlay, which, insofar as this is likely to remain serviceable for a long time, must be taken into account when determining the economical voltages.

If the load within an existing system increases, a check must first of all be made to ascertain whether the existing voltages will be adequate for higher power values or whether a higher voltage must be superimposed. In conjunction with these decisions, studies must also be carried out to determine whether in the superimposing of a higher voltage intermediate voltages (see table 1) can be completely or partly eliminated or whether voltages must be changed. On account of the existing plant, it is frequently impossible to select voltages and voltage steps which would be economical in a new scheme and, in working out the most advantageous overall long-term solution consideration has to be given to all conditions and factors involved. Actual practice has, however, shown that in many cases it is possible in existing systems to obtain appreciable reductions in costs by special planning, particularly with regard to the voltages used and their stepping.

In view of the multitude of factors which influence the selection of the voltage it has been possible to consider only the essential points and to draw from these conclusions as to the entire scheme. In every special case, however, comprehensive system planning should be carried out which includes both technical and economical aspects. This ensures that also as a long range policy more economical utilization is obtained of the capital to be invested in power supply.

/8. Summary

8. Summary

The economy of electrical power supply is determined essentially by the selection of the voltages in the distribution and transmission systems. Studies are made to determine which factors influence the selection of the voltage in the range of voltages over 1 kV. Fundamental considerations and examples provide directives for the voltages to be used in the medium and high-voltage ranges and also for their stepping. Special attention is paid to the influence of load density, transmission distance, and transmission power on the voltage to be selected. The steady growth of loads also makes it necessary that consideration be given to the load development which may not only vary with respect to time but also geographically. Matching of the voltages to the standardized values is also important.

The studies show that in the medium-voltage range no voltages below 10 kV should be used for new schemes. In cities with cable systems distribution voltages between 10 and 20 kV are economical, and in rural overhead systems voltages between 15 and 30 kV. In most cases a relationship of approximately 1:5 is suitable for the voltage step from the medium voltage to the superimposed high voltage. In special cases the economical voltage step may deviate sharply from this e.g., to higher values where very high load densities are involved or to low values where the rate of load growth in the system is relatively low.

In the selection of extra high voltages other special problems arise in the dimensioning of the insulation and design of the overhead lines. At high voltages the influence of the insulation on the costs may be of great importance, particularly where there is danger of contamination or other special climatic conditions obtain such as mountain climate. Recommendation are made for the dimensioning of the insulation, these being based on the new IEC Standards. Also important is the economical design of high-voltage overhead lines, since in long-distance transmission lines the proportion of the line costs to the total costs is very high. The factors influencing the costs of overhead lines are dealt with briefly.

In conclusion, it is point out that in the selection of the operating voltage all existing plant must be considered insofar as this is still serviceable. This sometimes prevents the most advantageous voltages from being introduced owing to the fact that the capital already invested in existing plant makes it uneconomical to change over to other voltages.

/Table 1

Table 1

VOLTAGE LEVELS AND THEIR RANGE OF APPLICATION

Voltage range	Designation	Range of application
Less than 1 kV	Low voltage	Distribution systems for feeding low-voltage consumers such as houses, small workshops, businesses, hotels.
1 to 35 kV	Medium voltage	Distribution systems for feeding low-voltage systems and large consumers such as chain stores, schools, hospitals, industrial plants, administration buildings, etc.
30 to 150 kV	High voltage a/	Distribution and transmission systems for feeding the medium-voltage systems, for cities, large industrial works, railways, district power supply.
More than 150 kV	Extra high voltage	Transmission systems for large blocks of power and for interconnected system operation.

a/ Where two high voltages are employed the lower one is designated the intermediate voltage.

/Table 2

Table 2

DIRECTIVES FOR THE MINIMUM CONDUCTOR DIAMETERS AND SURGE IMPEDANCES OF BUNDLE-CONDUCTOR LINES

Max. operating voltage U_m kV	Single or double circuit line	Mean conductor clearance m	Minimum conductor diameter in mm a/ number of sub-conductors				Surge impedance Z of each system in ohms number of sub-conductors			
			1	2	3	4	1	2	3	4
170	E	7	19 to 21	---	---	---	390	---	---	---
	D	5	19 to 21	---	---	---	375	---	---	---
245	E	9	28 to 30	19 to 21	---	---	385	295	---	---
	D	6	28 to 30	20 to 22	---	---	360	270	---	---
300	E	11	35 to 37	24 to 26	18 to 19	---	385	300	270	---
	D	7	35 to 37	25 to 27	19 to 20	---	355	270	245	---
420	E	14	51 to 53	34 to 36	25 to 27	20 to 22	375	305	280	260
	D	9	51 to 53	35 to 37	27 to 29	21 to 23	345	275	250	230
525 b/	E	16	---	44 to 46	33 to 35	26 to 28	---	305	280	260
	D	10	---	45 to 47	34 to 36	27 to 29	---	275	250	235

a/ Mean gradient at surface.
b/ Not yet laid down by IEC
E= Single
D= Double
Single-circuit line E_{rms} = 15 kV/cm.
Double-circuit line E_{rms} = 16 kV/cm

/Table 3

Table 3

ELECTRICAL CHARACTERISTICS OF SINGLE-CIRCUIT LINES ON WHICH THE CALCULATION OF THE COSTS IS BASED

Max. permissible operating voltage kV	Number and diameter of the conductors mm	Aluminium cross-section mm^2	Resistance at 60° Ω/km	Surge impedance Z Ω	Natural current I_{nat} A	Natural power P_{nat} MW	Max. thermal capacity P_{therm} MW	Related costs of the line per km %
123	1x19.2	184	0.180	390	170	35	85	100
245	1x28.1	341	0.097	390	343	140	250	175
420	2x32.8	2x564	0.029	310	750	520	1 200	320

/Table 4

Table 4

DIRECTIVES OF THE IEC FOR INSULATION CO-ORDINATION a/

Maximum permissible operating voltage U_m kV	Earthing coefficient (maximum)	$U_{e(m)}$ b/ kV	Full or reduced insulation	Impulse withstand voltage with full wave c/		A.C. withstand voltage (rms value)		Minimum clearances in air mm
				to earth and between the conductors kV	Across open contacts of isolating switches kV	to earth and between the conductors kV	Across open contacts of isolating switches kV	
123	0.8	98	123r	450	520	185	250	920
	1.0	123	123f	550	630	230	310	1 150
145	0.8	116	145r	550	630	230	310	1 150
	1.0	145	145f	650	750	275	370	1 380
170	0.8	136	170r	650	750	275	370	1 380
	1.0	170	170f	750	860	325	440	1 620
245	0.8	196	170r	900	1 035	395	535	1 960
	1.0	245	170f	1 050	1 210	460	620	2 300
300	0.8	240	300r	1 050	1 210	460	620	2 300
420	0.8	336	420r	1 425	...	630	...	3 050

a/ According to publication 71/2 (1958 edition)

b/ $U_{e(m)}$ = Maximum voltage to earth at operating frequency on fault.

c/ Available only as draft.

/FIGURE I

FIGURE I

GRAFICO I

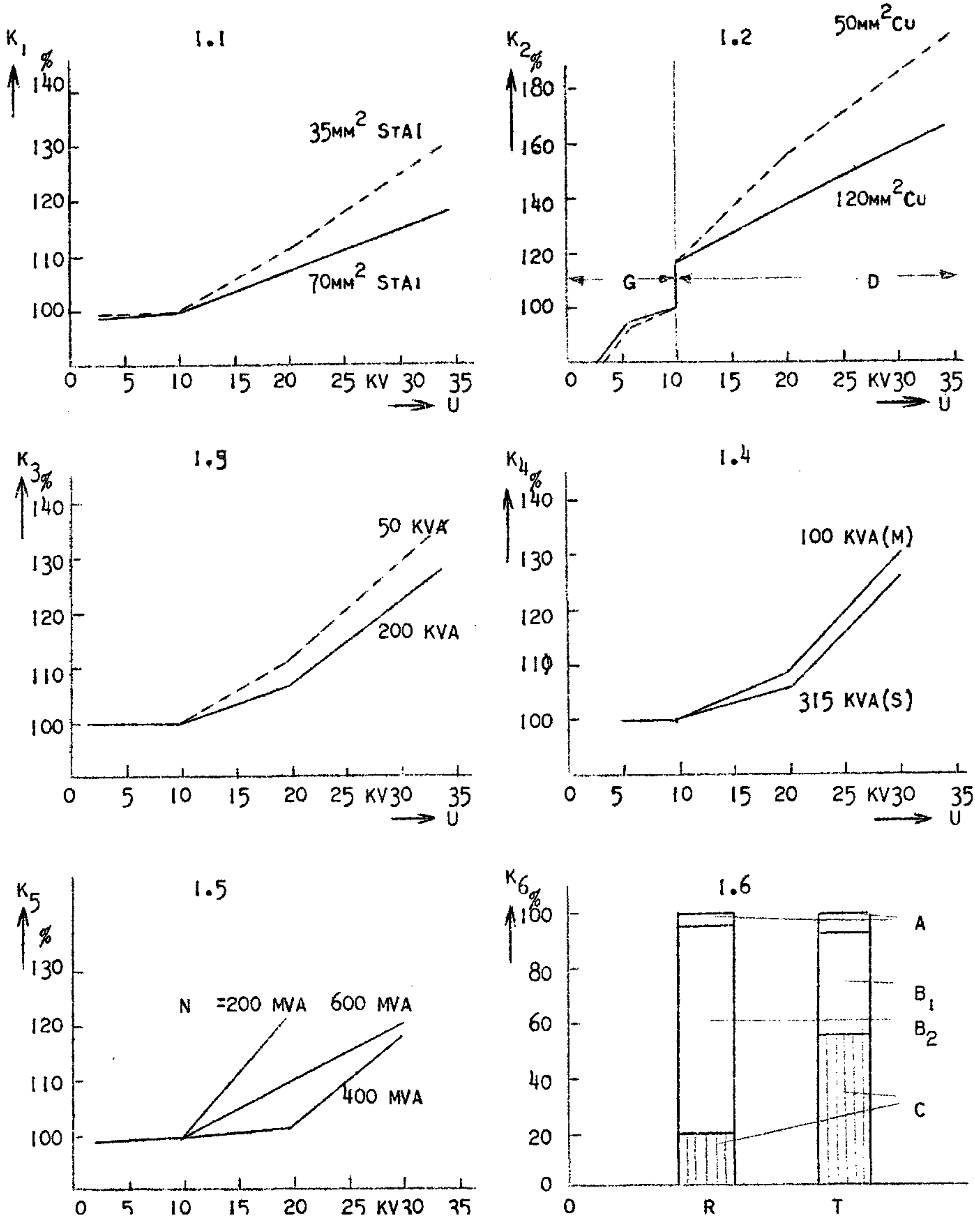

FIGURE II

GRAFICO II

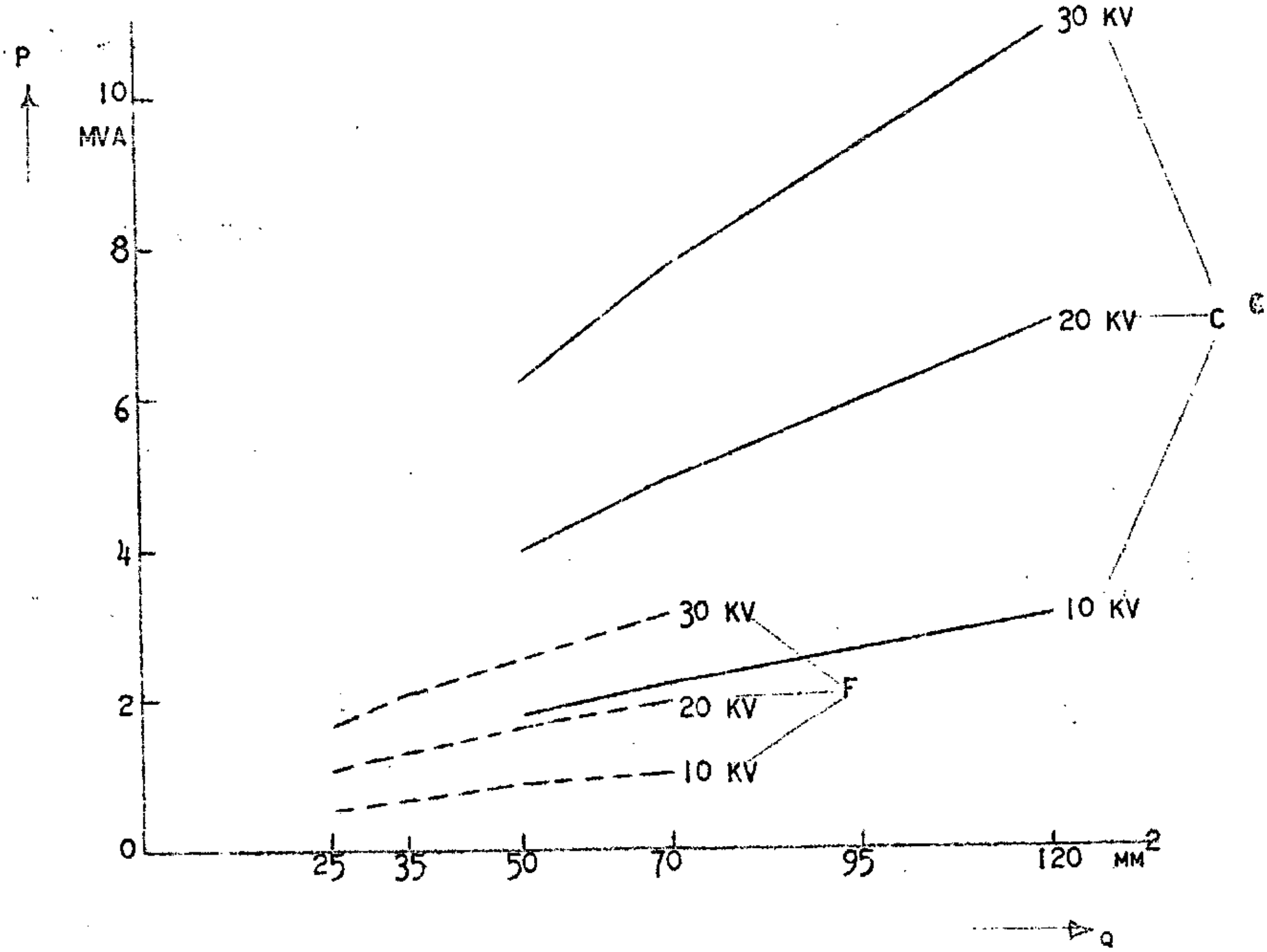

FIGURE III

GRAFICO III

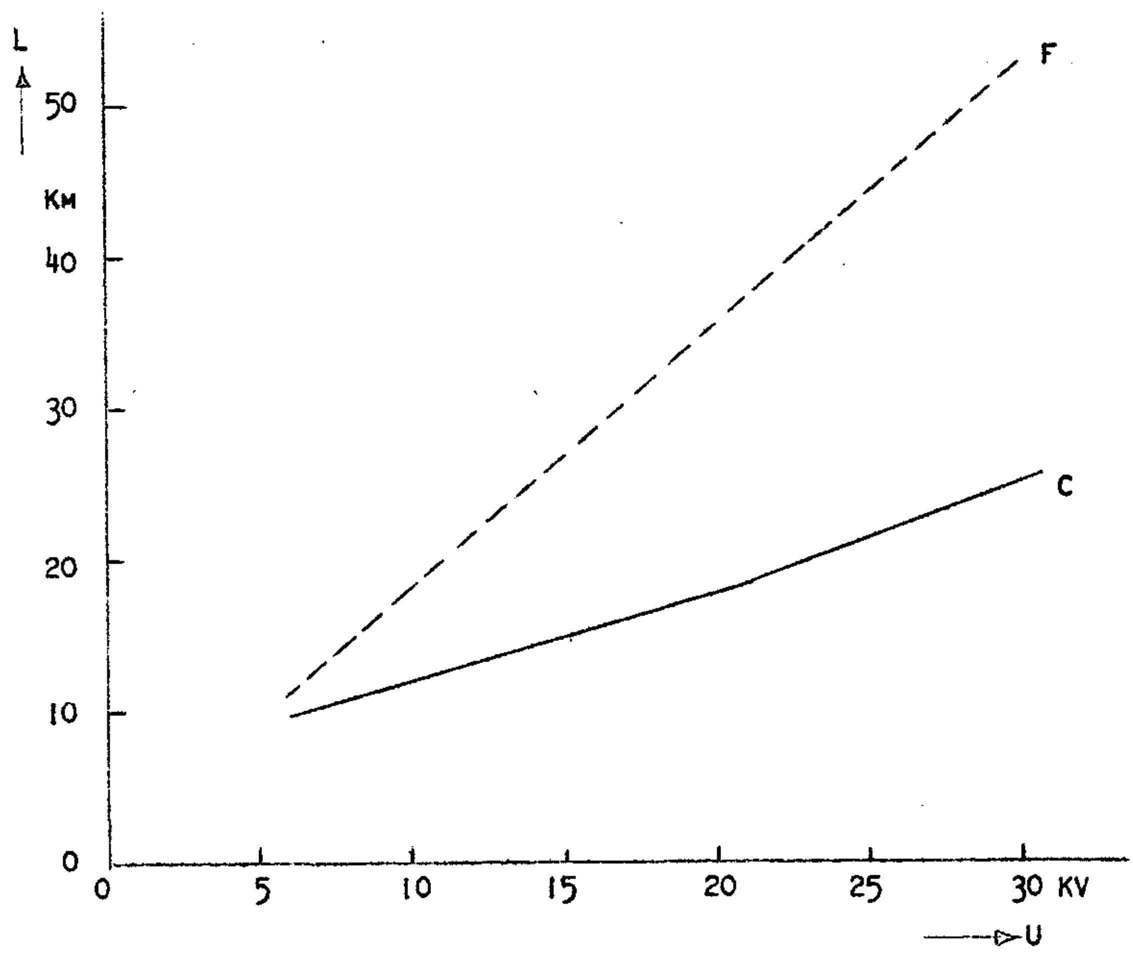

FIGURE IV

GRAFICO IV

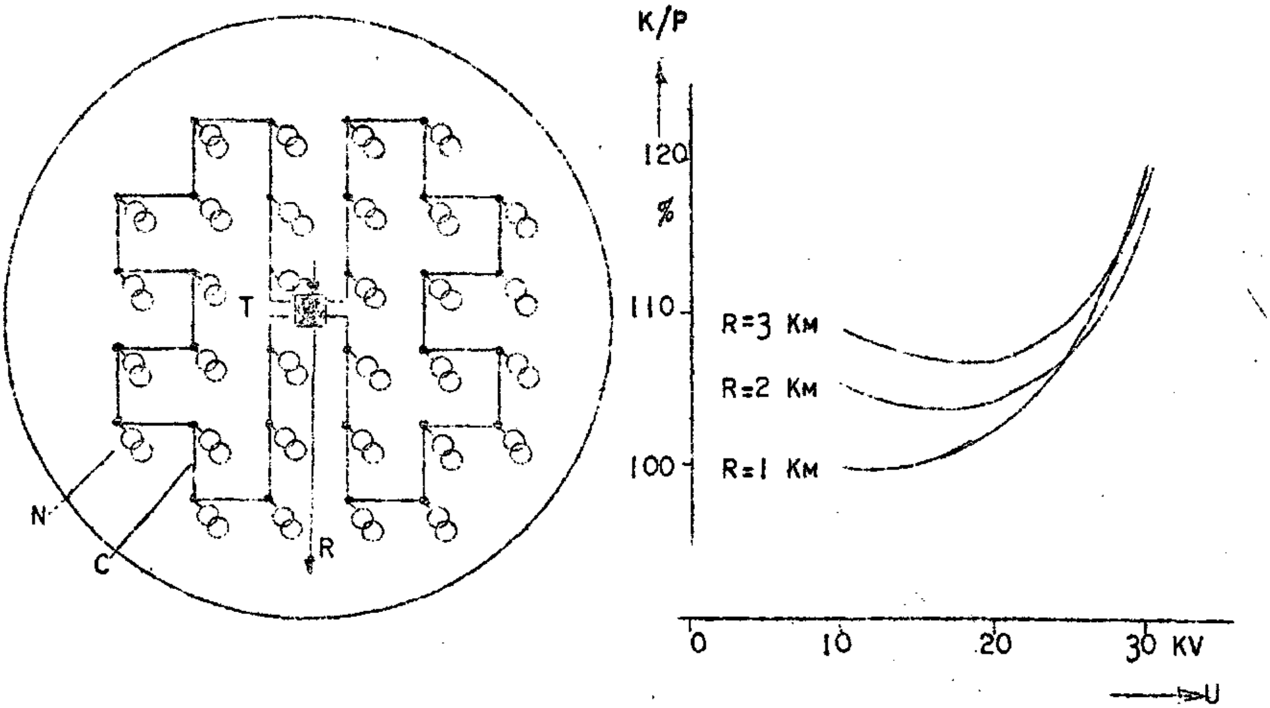

FIGURE V

GRAFICO V

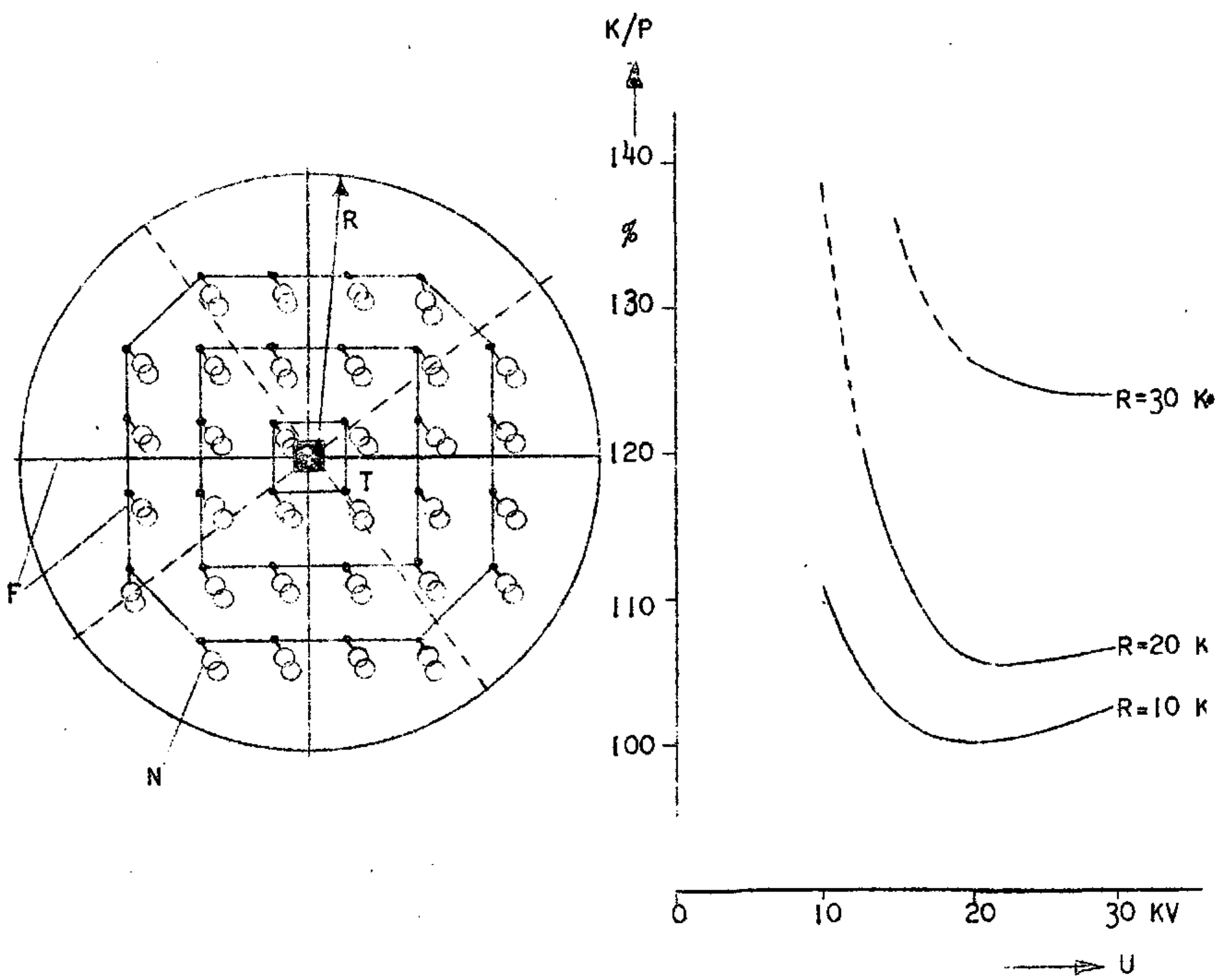

FIGURE VI A
GRAFICO VI A

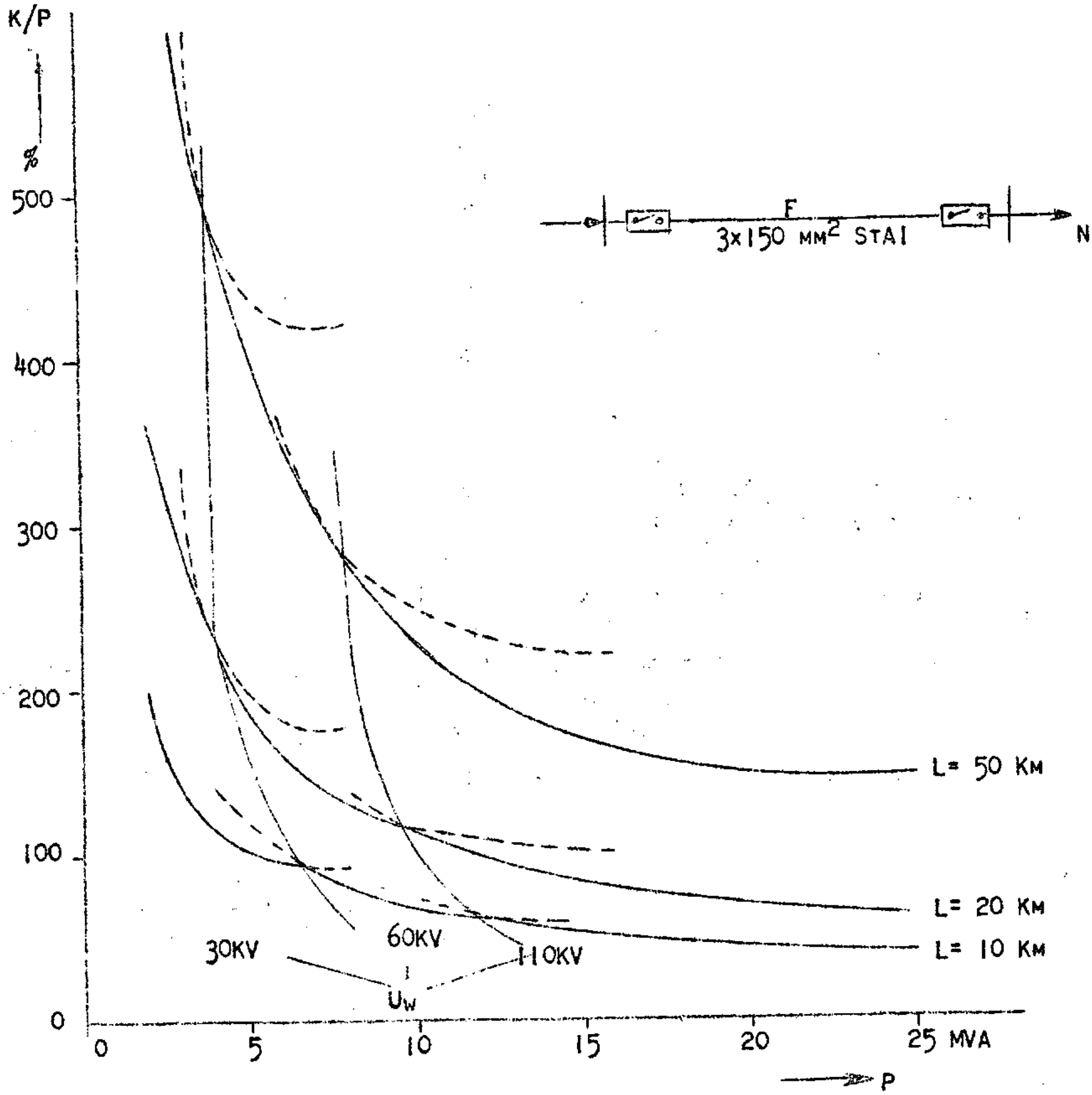

FIGURE VI B

GRAFICO VI B

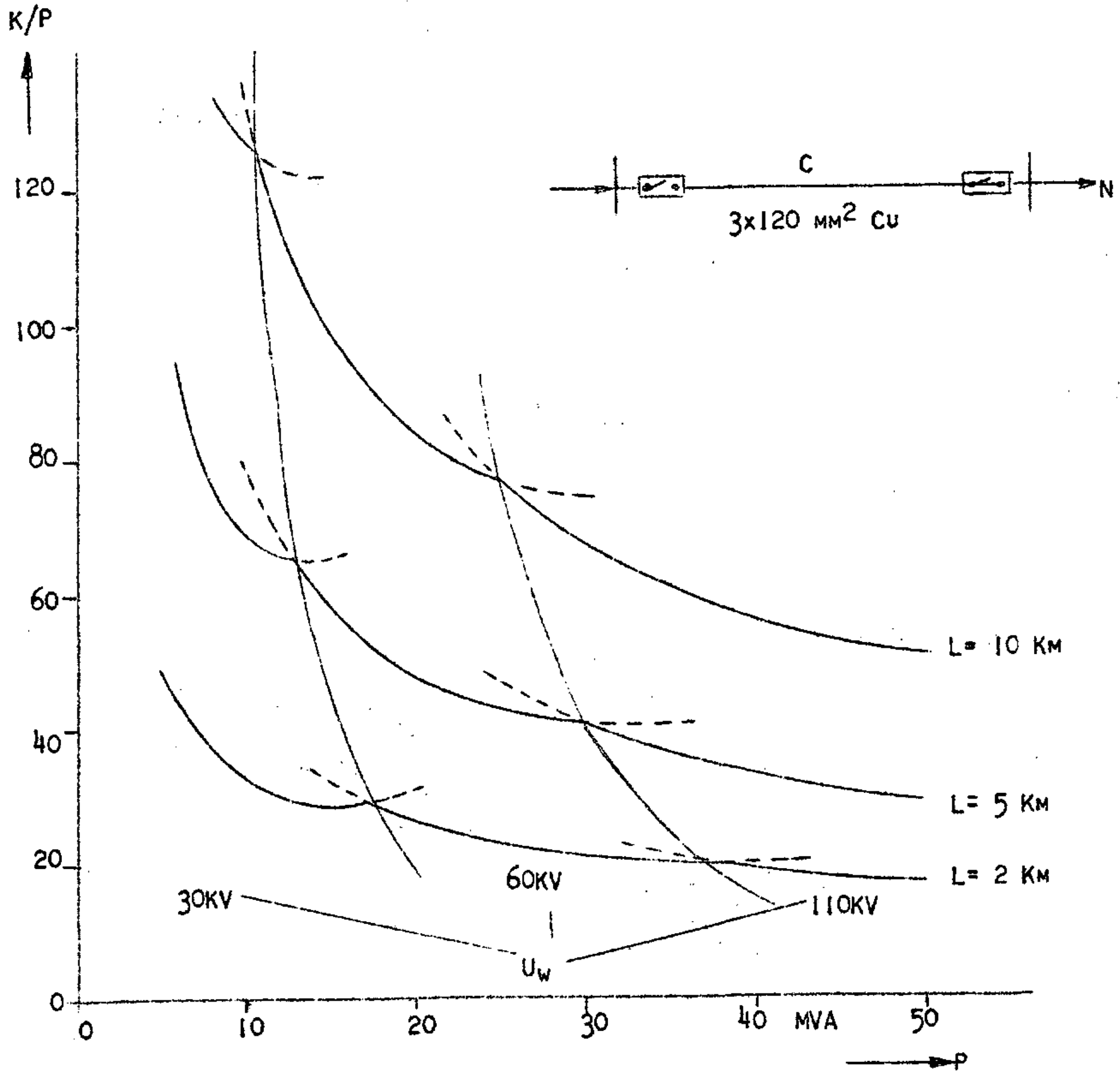

FIGURE VII

GRAFICO VII

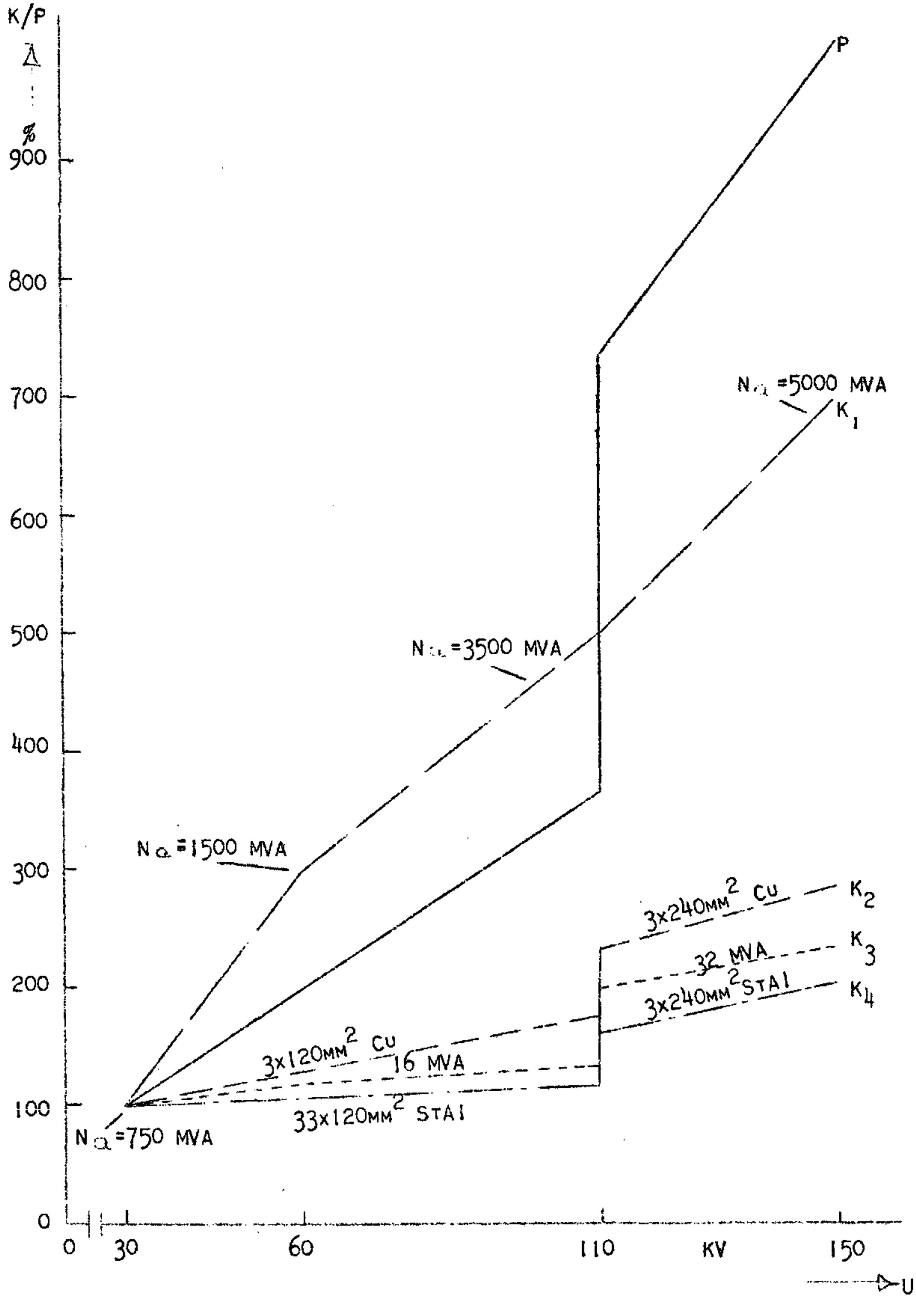

FIGURE VIII

GRAFICO VIII

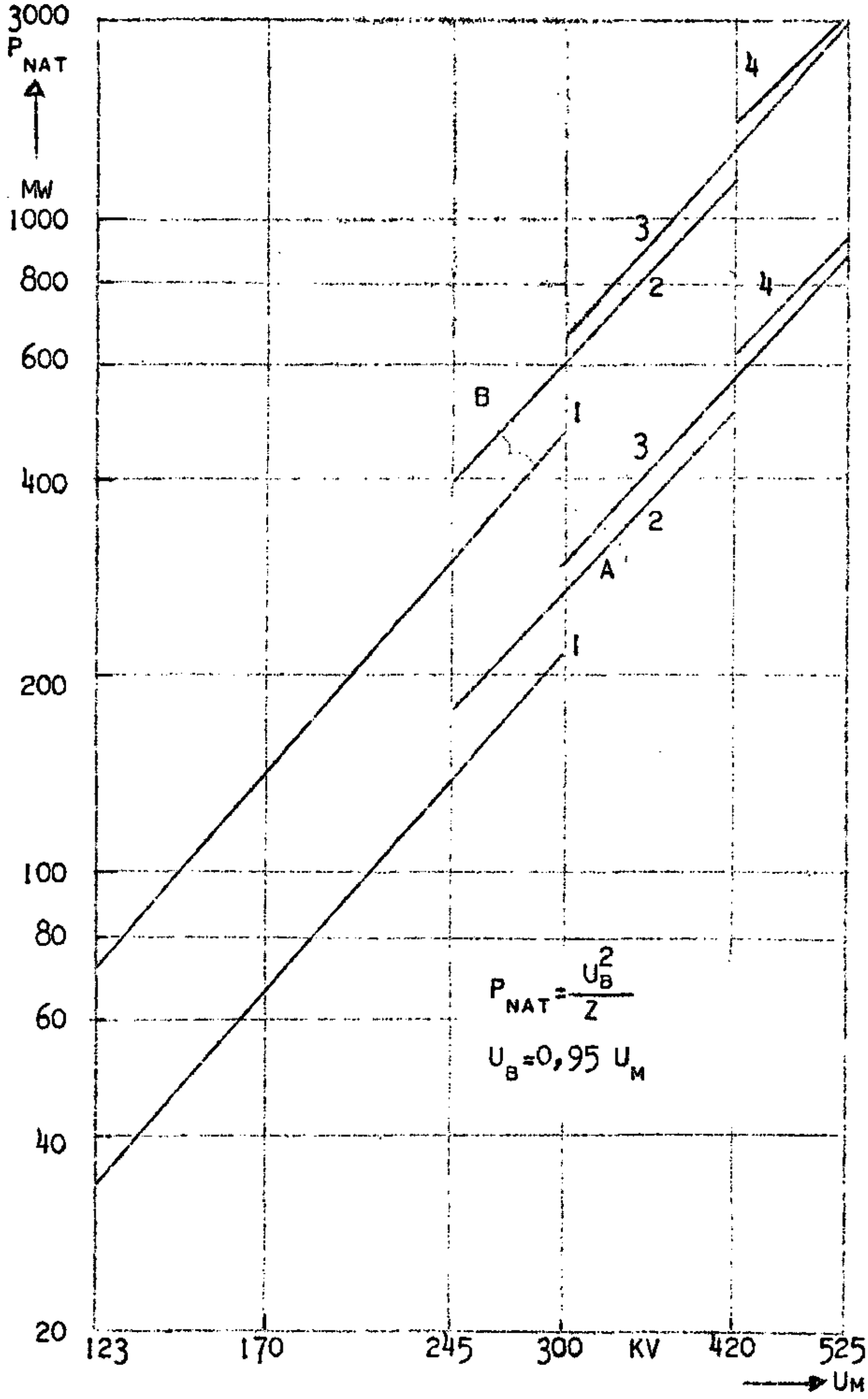

FIGURE IX

GRAFICO IX

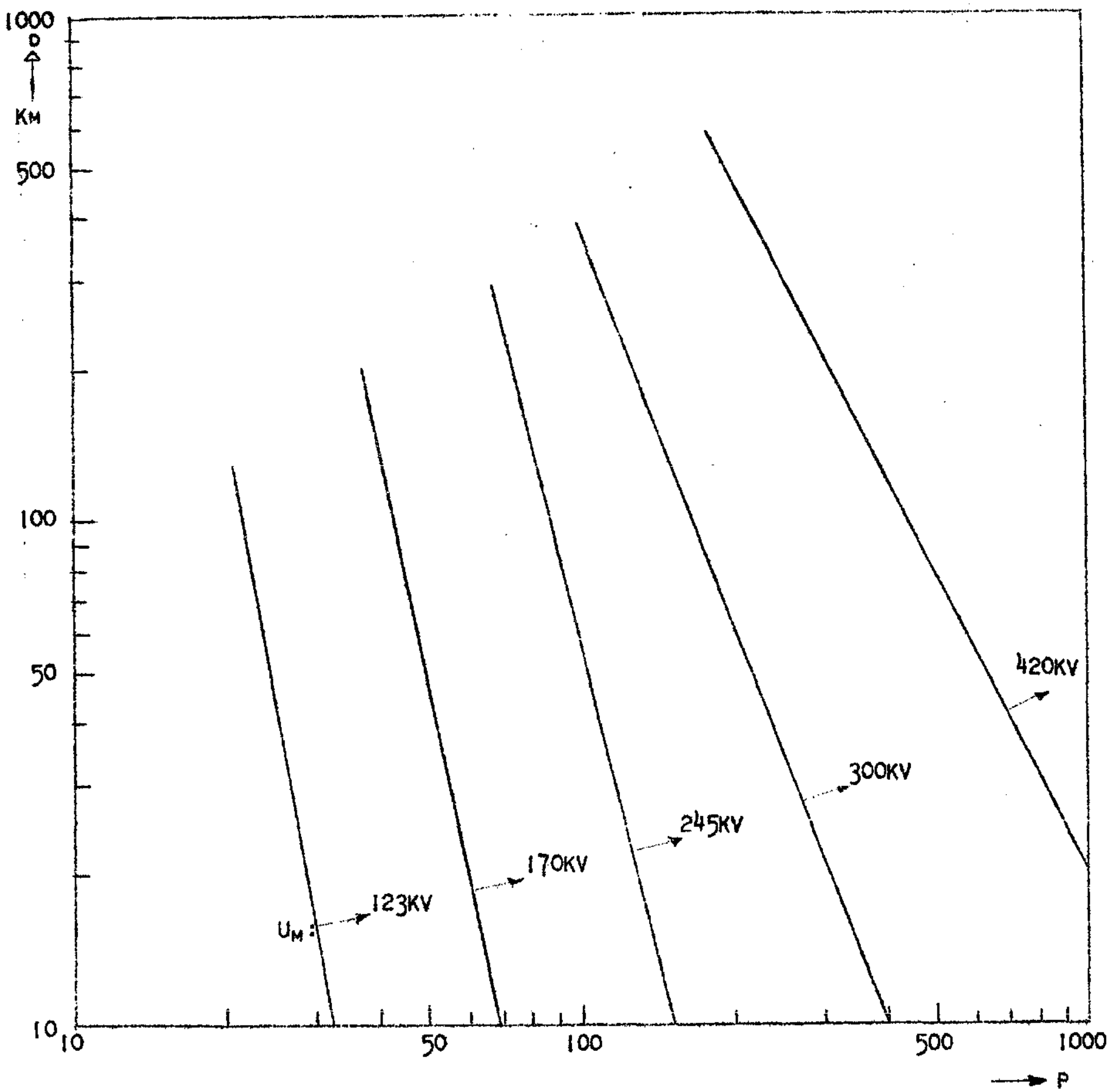

FIGURE X

GRAFICO X

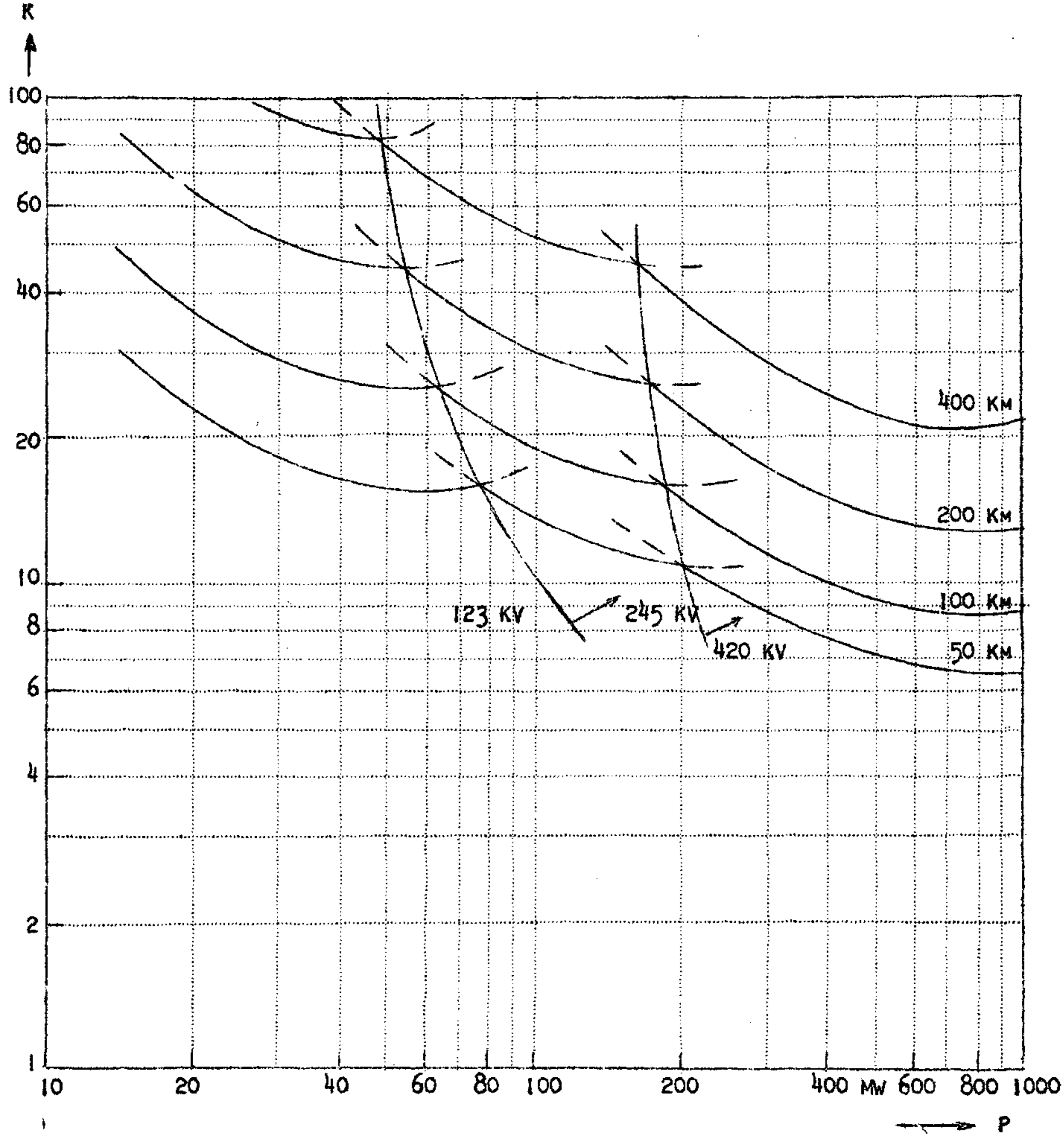

FIGURE XI

GRAFICO XI

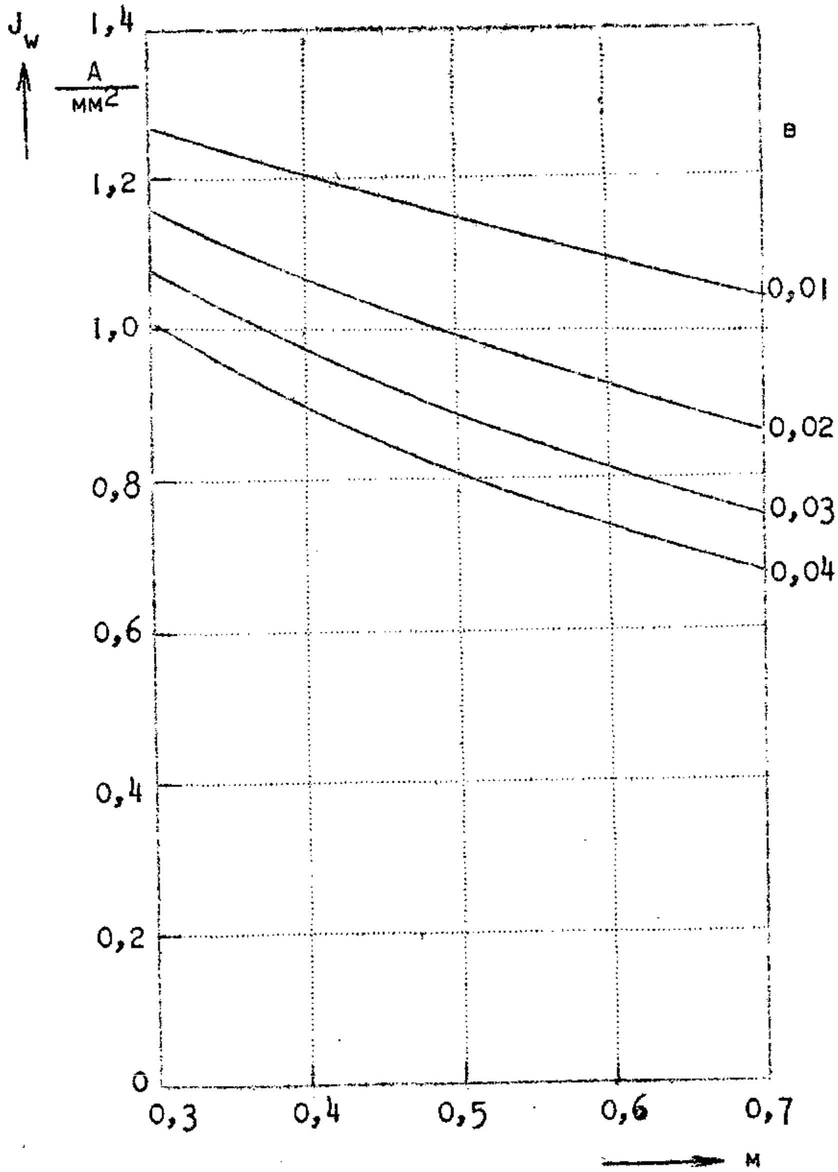

FIGURE XII

GRAFICO XII

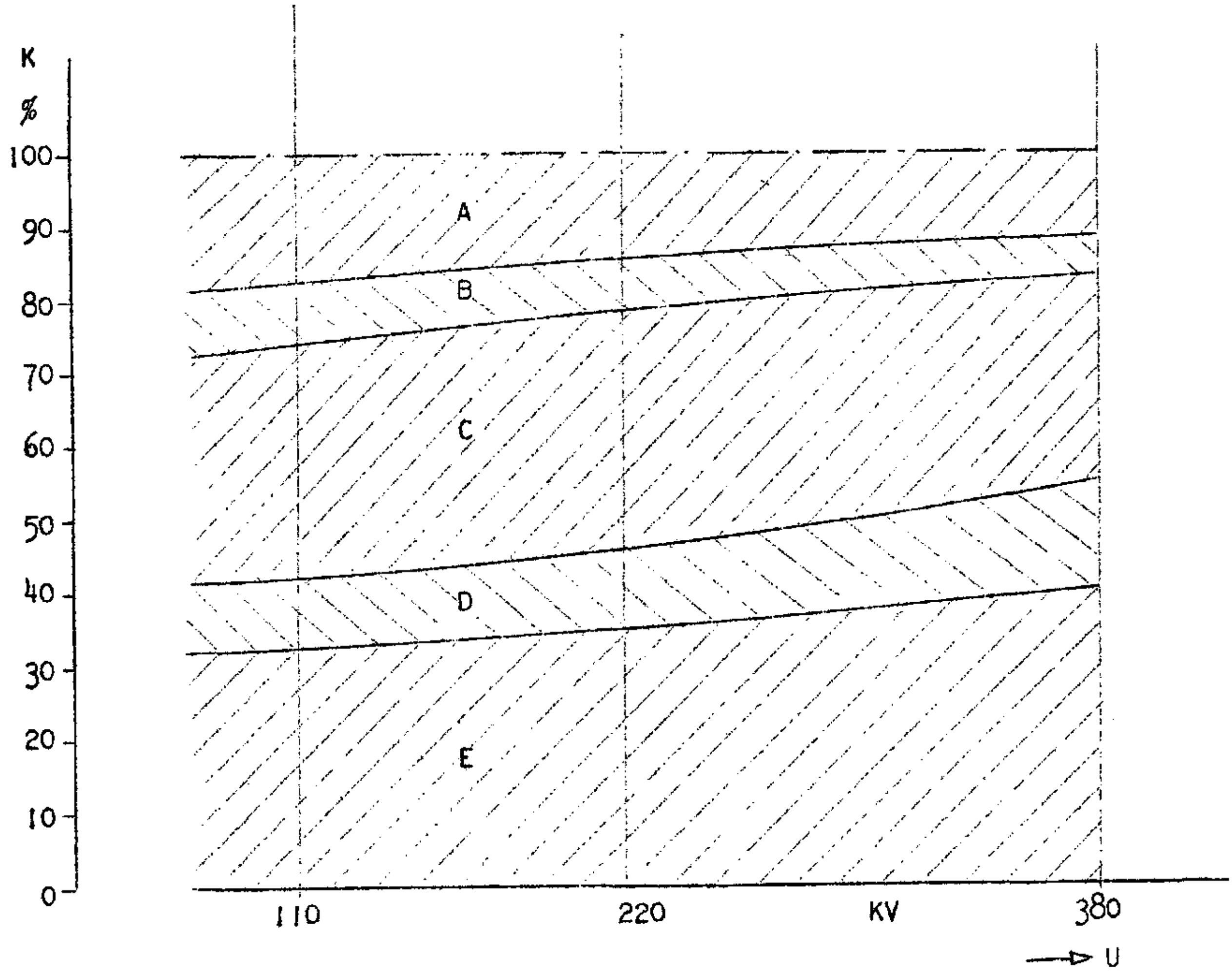

Fig. IX	Range of economical voltages as a function of the transmission power and the transmission distance
P	Transmission power per system
d	Transmission distance
U_m	Maximum permissible operating voltage

Fig. X	Annual transmission costs as a function of the transmission power and the transmission distance
P	Transmission power of each system
K	Annual transmission costs

Fig. XI	Economical current density of 245-kV overhead lines with steel-cored aluminium conductors as a function of the load factor and price per kWh
m	Load factor
j_w	Economical current density
b	Price per kWh

Fig. XII	Composition of the costs of high-voltage overhead lines
K	Costs (Total costs = 100%)
U	Rated voltage of the line
A	Costs of the erection of conductors and towers
B	Costs of foundations
C	Costs of towers
D	Costs of insulators and fittings
E	Costs of conductors

Fig. XIII	Optimum spans of overhead lines
K	Total costs of the overhead line
S_m	Average span
B	Concrete towers
G	Steel lattice towers
N	Normal soil
S	Poor soil