BRITISH STANDARD

BS 7450 : 1991
IEC 1059 : 1991

Method for

Determination of economic optimization of power cable size

(Implementation of CENELEC HD 558 S1)

STANDARDS

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Cables and Insulation Standards Policy Committee (CIL/-) to Technical Committee CIL/20, upon which the following bodies were represented:

Aluminium Federation
Association of Consulting Engineers
Association of Manufacturers of Domestic Electrical Appliances
British Approvals Service for Cables
British Cable Makers' Confederation
British Plastics Federation
British Steel plc
British Telecommunications plc
Department of the Environment (Property Services Agency)
Department of Trade and Industry (Consumer Safety United, CA Division)
ERA Technology Ltd.
Electricity Supply Industry in United Kingdom
Engineering Equipment and Materials Users' Association
Institution of Electrical Engineers
London Regional Transport

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

Electrical Contractors' Association
Institution of Incorporated Executive Engineers
London Underground Ltd.

This British Standard, having been prepared under the direction of the Cables and Insulation Standards Policy Committee, was published under the authority of the Standards Board and comes into effect on 28 June 1991

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Contents

National foreword

This British Standard has been prepared under the direction of the Cables and Insulation Standards Policy Committee. It is identical with IEC 1059 : 1991 'Economic optimization of power cable size' published by the International Electrotechnical Commission (IEC), which has been endorsed by CENELEC as HD 558 S1.

The Technical Committee has reviewed the provisions of IEC 228 : 1978, IEC 287 : 1982 and IEC 853, to which reference is made in the text, and has decided that they are acceptable for use in conjunction with this standard. A related British Standard to IEC 228 : 1978 is BS 6360 : 1981.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

INTRODUCTION

1 General part

The procedure generally used for the selection of a cable size leads to the minimum admissible cross-sectional area, which also minimizes the initial investment cost of the cable. It does not take into account the cost of the losses that will occur during the life of the cable.

The increasing cost of energy, together with the high energy losses which follow from the operating temperatures possible with the newer insulating materials (e.g. 90 °C for XLPE and EPR), now requires that cable size selection be considered on wider economic grounds. Rather than minimizing the initial cost only, the sum of the initial cost and the cost of the losses over the economic life of the cable should also be minimized. For this latter condition a larger size of conductor than would be chosen based on minimum initial cost will lead to a lower power loss for the same current and will, when considered over its economic life, be much less expensive.

The future costs of energy losses during the economic life of the cable can be calculated by making suitable estimates of load growth and cost of energy. The most economical size of conductor is achieved when the sum of the future costs of energy losses and the initial cost of purchase and installation are minimized.

The saving in overall cost, when a conductor size larger than that determined by thermal constraints is chosen, is due to the considerable reduction in the cost of the joule losses compared with the increase in cost of purchase. For the values of the financial and electrical parameters used in this standard, which are not exceptional, the saving in the combined cost of purchase and operation is of the order of 50 % (see clause A.6 in annex A). Calculations for much shorter financial periods can show a similar pattern.

A further important feature, which is demonstrated by examples, is that the savings possible are not critically dependent on the conductor size when it is in the region of the economic value, see figure A.3. This has two implications:

a) The impact of errors in financial data, particularly those which determine future costs, is small. While it is advantageous to seek data having the best practicable accuracy, considerable savings can be achieved using data based on reasonable estimates.

b) Other considerations with regard to the choice of conductor size which feature in the overall economics of an installation, such as fault currents, voltage drop and size rationalization, can all be given appropriate emphasis without losing too many of the benefits arising from the choice of an economic size.

2 Economic aspects

In order to combine the purchase and installation costs with costs of energy losses arising during the economic life of a cable, it is necessary to express them in comparable economic values, that is values which relate to the same point in time. It is convenient to use the date of purchase of the installation as this point and to refer to it as the "present". The "future" costs of the energy losses are then converted to their equivalent "present values". This is done by the process of discounting, the discounting rate being linked to the cost of borrowing money.

In the procedure given here inflation has been omitted on the grounds that it will affect both the cost of borrowing money and the cost of energy. If these items are considered over the same period of time and the effect of inflation is approximately the same for both, the choice of an economic size can be made satisfactorily without introducing the added complication of inflation.

To calculate the present value of the costs of the losses it is necessary to choose appropriate values for the future development of the load, annual increases in kWh price and annual discounting rates over the economic life of the cable, which could be 25 years or more. It is not possible to give guidance on these aspects in this standard because they are dependent on the conditions and financial constraints of individual installations. Only the appropriate formulae are given: it is the responsibility of the designer and the user to agree on the economic factors to be used.

The formulae proposed in this standard are straightforward, but in their application due regard should be taken of the assumption that the financial parameters are assumed to remain unchanged during the economic life of the cable. Nevertheless, the above comments on the effect of the accuracy of these parameters is relevant here also.

There are two approaches to the calculation of the economic size, based on the same financial concepts. The first, where a series of conductor sizes is being considered, is to calculate a range of economic currents for each of the conductor sizes envisaged for particular installation conditions and then to select that size whose economic range contains the required value of the load. This approach is appropriate where several similar installations are under consideration. The second method, which may be more suitable where only one installation is involved, is to calculate the optimum cross-sectional area for the required load and then to select the closest standard conductor size.

3 Other criteria

Other criteria, for example short-circuit current and its duration, voltage drop and cable size rationalization, must be considered also. However, a cable chosen to have an economical size of conductor may well be satisfactory also from these other points of view, so that when sizing a cable the following sequence may be advantageous:

a) calculate the economic cross-sectional area;

b) check by the methods given in IEC 287 and IEC 853 that the size indicated by a) is adequate to carry the maximum load expected to occur at the end of the economic period without its conductor temperature exceeding the maximum permitted value;

c) check that the size of cable selected can safely withstand the prospective short-circuit and earth fault currents for the corresponding durations;

d) check that the voltage drop at the end of the cable remains within acceptable limits;

e) check against other criteria appropriate to the installation.

To complete the field of economic selection, proper weight should be given to the consequences of interruption of supply. It may be necessary to use a larger cross-section of conductor than the normal load conditions require and/or the economic choice would suggest, or to adapt the network accordingly.

A further cost component may be recognized in the financial consequence of making a faulty decision weighted by its probability. However, in doing so one enters the field of decision theory which is outside the scope of this standard.

Thus, economic cable sizing is only a part of the total economic consideration of a system and may give way to other important economic factors.

ECONOMIC OPTIMIZATION OF POWER CABLE SIZE

1 Scope

This International Standard deals solely with the economic choice of conductor size based on joule losses. Voltage dependent losses have not been considered.

NOTES

1 It is recommended that the method given in this standard should not be used for cables operating on system voltages equal to or greater than the following (see IEC 287):

Type of cable	*System voltage U_0* kV
Cables insulated with impregnated paper:	
solid type	38
oil-filled and gas pressure	63,5
Cables with other types of insulation:	
butyl rubber	18
EPR	63,5
PVC	6
PE (HD and LD)	127
XLPE (unfilled)	127
XLPE (filled)	63,5

2 Modifications to the method given in this standard in order to take dielectric losses into account are under consideration.

Likewise, matters such as maintenance, energy losses in forced cooling systems and time of day energy costs have not been included in this standard.

An example of the application of the method to a hypothetical supply system is given in annex A.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 228: 1978, *Conductors of insulated cables.*

IEC 287: 1982, *Calculation of the continuous current rating of cables (100 % load factor).*

IEC 853, *Calculation of the cyclic and emergency current rating of cables.*

3 Symbols

A	= variable component of cost per unit length related to conductor size	cu/m.mm^2
B	= auxiliary quantity defined by equation (16)	–
C	= constant component of cost per unit length related to laying conditions etc.	cu/m
CT	= total cost of a system	cu
D	= demand charge each year	cu/W.year
F	= auxiliary quantity defined by equation (10)	cu/W
I_{max}	= maximum load in first year i.e. the highest hourly mean value	A
$I(t)$	= load as a function of time	A
l	= cable length	m
CJ	= present value of the cost of joule losses during N years	cu
N	= period covered by financial calculations, also referred to as "economic life"	year
N_p	= number of phase conductors per circuit	–
N_c	= number of circuits carrying the same type and value of load	–
P	= cost of one watt-hour at relevant voltage level	cu/W.h
CI	= installed cost of the length of cable being considered	cu
CI_2	= installed cost of the next larger standard size of conductor	cu
CI_1	= installed cost of the next smaller standard size of conductor	cu
$CI(S)$	= installed cost of a cable as a function of its cross-sectional area	cu
Q	= auxiliary quantity defined by equation (8)	–
R	= cable a.c. resistance per unit length, including the effect of y_p, y_s, λ_1, λ_2,(considered to be a constant value at an average operating temperature, see clause 4)	Ω/m
R_2	= a.c. resistance per unit length of next larger standard conductor size	Ω/m

R_1 = a.c. resistance per unit length of next smaller standard conductor size Ω/m

$R(S)$ = a.c. resistance per unit length of a conductor as a function of its area Ω/m

S = cross-sectional area of a cable conductor mm^2

S_{ec} = economic conductor size mm^2

T = operating time at maximum joule loss h/year

a = annual increase in I_{max} %

b = annual increase in P, not covered by inflation %

i = discounting rate used to compute present values %

r = auxiliary quantity defined by equation (9) –

t = time h

y_p = proximity effect factor, see IEC 287 –

y_s = skin effect factor, see IEC 287 –

α_{20} = temperature coefficient of conductor resistance at 20 °C 1/K

θ = maximum rated conductor operating temperature °C

θ_a = ambient average temperature °C

θ_m = mean operating conductor temperature °C

λ_1, λ_2 = sheath and armour loss factors, see IEC 287 –

μ = loss load factor, see IEC 853 –

ρ_{20} = conductor resistivity at 20 °C, see 5.2 Ω.m

4 Calculation of total costs

The total cost of installing and operating a cable during its economic life, expressed in present values, is calculated as follows. Note that all financial quantities are expressed in arbitrary currency units, (cu).

$$\text{The total cost} = CT = CI + CJ \text{ (cu)} \qquad (1)$$

where

CI = the cost of the installed length of cable, cu;

CJ = the equivalent cost at the date the installation was purchased, i.e. the present value, of the joule losses during an economic life of N years, cu.

Evaluation of CJ

The total cost due to the losses is composed of two parts: a) the energy charge and b) the charge for the additional supply capacity to provide the losses.

a) *Cost due to energy charge*

$$\text{Energy loss during the first year} = (I^2_{\max} . R . l . N_p . N_c) T \ \text{(W.h)} \tag{2}$$

where

$I_{\max}$ = maximum load on the cable during the first year, A;

l = length of cable, m;

R = apparent a.c. resistance of a conductor per unit length, taking into account both skin and proximity effects (y_p, y_s) and losses in metal screens and armour (λ_1,λ_2), Ω/m.

As the economic conductor size is usually larger than the size based on thermal considerations (i.e. the size determined by the use of IEC 287 and/or IEC 853), its temperature will be lower than the maximum permissible value. It is convenient to assume, in the absence of more precise information, that R is constant and has a value corresponding to a temperature of $(\theta-\theta_a)/3 + \theta_a$.

Here θ is the maximum rated conductor temperature for the type of cable concerned and θ_a is the ambient average temperature. Factor 3 is empirical, see annex B.

NOTE - If greater precision is required (for example where the calculations do not indicate clearly which nominal conductor size should be chosen or the growth in load is such that its value during the final years is significantly higher than that of the first year) a better estimate of conductor temperature can be made using as a starting point the conductor size obtained from the approximate temperature given above.

Methods for making a more refined estimate of conductor temperature and resistance are given in annex B. The economical size is then redetermined using the revised value of conductor resistance.

The effect of conductor resistance on the value of the economical size is small and it is seldom worthwhile to perform the iteration more than once.

N_p = number of phase conductors per circuit;

N_c = number of circuits carrying the same value and type of load;

T = operating time at maximum joule loss, h/year;

= number of hours per year that the maximum current $I_{\max}$ would need to flow in order to produce the same total yearly energy losses as the actual, variable, load current;

$$T = \int_0^{8\,760} \frac{I(t)^2 \cdot dt}{I^2_{\max}}.$$

If the loss load factor μ is known and can be assumed to be constant during the economic life, then:

T = $\mu . 8\,760$

See IEC 853 for the derivation of the loss load factor, μ;

t = time, h;

$I(t)$ = load current as a function of time, A.

The cost of the first year's losses is:

$$= (I^2_{max}.R.l.N_p.N_c).T.P \quad \text{(cu)} \qquad (3)$$

where

P = cost of one watt-hour of energy at the relevant voltage level, cu/W.h.

b) *Cost due to additional supply capacity*

The cost of additional supply capacity to provide these losses is:

$$= (I^2_{max}.R.l.N_p.N_c).D \quad \text{(cu/year)} \qquad (4)$$

where

D = demand charge per year, cu/W.year.

The overall cost of the first year's losses is therefore:

$$= (I^2_{max}.R.l.N_p.N_c).(T.P + D) \quad \text{(cu)} \qquad (5)$$

If costs are paid at the end of the year, then at the date of the purchase of the installation their present value is:

$$= \frac{(I^2_{max}.R.l.N_p.N_c).(T.P + D)}{(1 + i/100)} \quad \text{(cu)} \qquad (6)$$

where

i = discount rate, not including the effect of inflation, %.

Similarly, the present value of energy costs during N years of operation, discounted to the date of purchase is:

$$CJ = (I^2_{max}.R.l.N_p.N_c).(T.P + D). \frac{Q}{(1 + i/100)} \quad \text{(cu)} \qquad (7)$$

where

Q = a coefficient taking into account the increase in load, the increase in cost of energy over N years and the discount rate.

$$= \sum_{n=1}^{N} (r^{n-1}) = \frac{1 - r^N}{1 - r} \qquad (8)$$

$$r = \frac{(1 + a/100)^2 . (1 + b/100)}{(1 + i/100)} \qquad (9)$$

and

a = increase in load per year, %;

b = increase in cost of energy per year, not including the effect of inflation, %.

Where a number of calculations involving different sizes of conductor are required, it is advantageous to express all the parameters excepting conductor current and resistance in one coefficient F, where

$$F = N_p.N_c.(T.P + D).\frac{Q}{(1 + i/100)} \quad \text{(cu/W)} \tag{10}$$

The total cost is then given by:

$$CT = CI + I^2_{\max}.R.l.F \text{ (cu)} \tag{11}$$

5 Determination of economic conductor sizes

5.1 *First approach: economic current range for each conductor in a series of sizes*

All conductor sizes have an economic current range for given installation conditions. The upper and lower limits of the economic range for a given conductor size are given by:

$$\text{lower limit of } I_{\max} = \sqrt{\frac{CI - CI_1}{F.l.(R_1 - R)}} \quad \text{(A)} \tag{12}$$

$$\text{upper limit } I_{\max} = \sqrt{\frac{CI_2 - CI}{F.l.(R - R_2)}} \quad \text{(A)} \tag{13}$$

where

CI = installed cost of the length of cable whose conductor size is being considered, cu;

R = a.c. resistance per unit length of the conductor size being considered, Ω/m;

CI_1 = installed cost of the next smaller standard conductor, cu;

R_1 = a.c. resistance per unit length of the next smaller standard conductor, Ω/m;

CI_2 = installed cost of the next larger standard conductor, cu;

R_2 = a.c. resistance per unit length of the next larger standard conductor, Ω/m.

NOTES

1 The upper and lower economic current limits of each conductor size may be tabulated and used to select the most economic size of conductor for a particular load.

2 The upper economic current limit of one conductor size is the lower economic current limit for the next larger conductor size.

5.2 *Second approach: economic conductor size for a given load*

5.2.1 *General equation*

The economic conductor size, S_{ec} is the cross-section that minimizes the total cost function:

$$CT(S) = CI(S) + I_{max}^2 . R(S) . \ell . F \quad \text{(cu)} \tag{14}$$

where $CI(S)$ and $R(S)$ are expressed as functions of the conductor cross-section S, see 5.2.2.

The equation for the relationship between $CI(S)$ and conductor size can be derived from known costs of standard cable sizes. In general, if a reasonably linear relationship can be fitted to the costs, possibly over a restricted range of conductor sizes, it should be used. This will cause little error in the results, in view of the possible uncertainties in the assumed financial parameters for the economic life period chosen.

According to IEC 287, the apparent conductor resistance can be expressed as a function of the cross-section by:

$$R(S) = \frac{\rho_{20} . B\,[1 + \alpha_{20}(\theta_m - 20)]}{S} \times 10^6 \quad (\Omega/\text{m}) \tag{15}$$

$$B = (1 + y_p + y_s)\,(1 + \lambda_1 + \lambda_2) \tag{16}$$

where

ρ_{20} = d.c. resistivity of the conductor, Ω.m.

NOTE - The economic conductor size is unlikely to be identical to a standard size and so it is necessary to provide a continuous relationship between resistance and size. This is done by assuming a value of resistivity for each conductor material. The values recommended here for ρ_{20} are: $18{,}35 \times 10^{-9}$ for copper and $30{,}3 \times 10^{-9}$ for aluminium. These values are not the actual values for the materials, but are compromise values chosen so that conductor resistances can be calculated directly from nominal conductor sizes, rather than from the actual effective cross-sectional areas.

y_p, y_s = skin and proximity effect factors, see IEC 287;

λ_1, λ_2 = sheath and armour loss factors, see IEC 287;

α_{20} = temperature coefficient of resistivity for the particular conductor material at 20 °C, K^{-1};

θ_m = conductor temperature, see explanation given in the definition of R for equation (2), °C;

B = auxiliary value defined by equation (16), which can be calculated from IEC 287 by assuming a probable value for the economic size of conductor;

S = cross-sectional area of cable conductor, mm².

5.2.2 *Linear cost function for cable costs*

If a linear model can be fitted to the values of initial cost for the type of cable and installation under consideration, then:

$$CI(S) = l.(A.S + C) \text{ (cu)} \tag{17}$$

where

A = variable component of cost, related to conductor size, cu/m.mm²;

C = constant component of cost, unaffected by size of cable, cu/m;

l = length of cable, m.

Then the optimum size S_{ec} (mm²) can be obtained by equating to zero the derivative of equation (14) with respect to S, giving:

$$S_{ec} = 1\,000 \left[\frac{I^2_{max} . F . \rho_{20} . B [1 + \alpha_{20}(\theta_m - 20)]}{A} \right]^{0,5} \text{ (mm}^2\text{)} \tag{18}$$

NOTES

1 As the economic size is unknown, it is necessary to make an assumption as to the probable cable size in order that reasonable values of y_p, y_s, λ_1 and λ_2, can be calculated. Recalculation may be necessary if the economic size is too different.

2 The constant component of the cost, C, in equation (17), does not affect the evaluation of the economic size S_{ec}.

S_{ec} is unlikely to be exactly equal to a standard size (see IEC 228) and so the cost for the adjacent larger and smaller standard sizes shall be calculated and the most economical one chosen.

Annex A
(informative)

Examples of calculation of economic conductor sizes

A.1 General

Example calculations are given for a supply system feeding ten equal loads uniformly spaced along a route for the following cases:

a) An application of the first approach (see 5.1), the economic current range method, to size each cable between adjacent loads.

b) An application of the second method (see 5.2), the economic conductor size method, to size each cable between adjacent loads.

c) An application of both methods to give the most economical conductor size where only one size of cable is used throughout the whole route.

The results are summarized in A.6 to show the saving that can be obtained by choosing a conductor size which reduces the overall costs, rather than by minimizing the first cost.

A.2 Cable and supply system details

Load and route data

A 10 kV cable circuit has to be sized to supply ten 10 kV/0,4 kV substations equally spaced along a route from a 150 kV/10 kV station (see figure A.1). (There is only one three-phase circuit so $N_c = 1$ and $N_p = 3$.)

The cable length between substations is 500 m.

The highest hourly mean values of current I_{max}, in the first year for each section of the route are:

Section	Current (A)
1	160
2	144
3	128
reducing by 16 A at each station to:	
9	32
10	16

The cyclic rating factor, M, for all loads is 1,11 (see IEC 853). It is assumed that this factor remains constant during the economic life of the cable.

For each section of the route the cable size is chosen according to the following criteria:

a) The minimized sum of the primary cost plus the present value of the joule losses for the economic life of the cable.

b) The current-carrying capacity required for the load during the last year of the economic life of the cable. The required current-carrying capacity for this example is 0,9 times the maximum load, i.e. the maximum load divided by the cyclic rating factor of 1,11.

c) Other factors, such as short-circuit withstand and voltage drop, have not been considered in this example, but can be introduced as indicated in clause 3 of the introduction to this standard.

Financial data

economic life	N	30	(year)
operating time at maximum loss (the value of 2 250 includes the effect or the daily cyclic load)	T	2 250	(h/year)
price of joule losses at end of first year at 10 kV	P	$60{,}9 \times 10^{-6}$	(cu./W.h)
demand charges	D	0,003	(cu/W.year)
cable and installation costs per unit length are given in table A.1			(cu/m)
For this example, the coefficient of that part of the installation costs which depends on conductor size has been calculated to be	A	0,1133	(cu/m.mm²)
annual increase of load	a	0,5	(%)
annual increase of cost of energy (kW.h price)	b	2,0	(%)
annual discounting rate	i	5,0	(%)

Cable data

For the purpose of this example a fictional three-core 6/10 kV type of cable has been assumed. The a.c. resistances of the conductors at 40 °C and 80 °C are given in columns (2) and (3) of table A.1 and the financial details are given in columns (4) to (6). It has a permissible maximum conductor temperature of 80 °C and when laid in the ground the steady-state ratings at this temperature, for a 20 °C ground ambient temperature, are those given in A.3.3.

Calculation of auxiliary quantities

$$r = \frac{[1 + (0{,}5/100)]^2 \times [1 + (2/100)]}{1 + (5/100)} = 0{,}98117 \qquad \text{(equation 9)}$$

$$Q = \frac{1 - 0{,}9812^{30}}{1 - 0{,}9812} = 23{,}081 \qquad \text{(equation 8)}$$

$$F = \frac{3 \times 1 \times (2\,250 \times 60{,}9 \times 10^{-6} + 0{,}003) \times 23{,}08}{1 + (5/100)} = 9{,}2341 \quad \text{(equation 10)}$$

A.3 Calculation using the economic current range method (see 5.1)

A.3.1 *Calculation of the economic current range of one size*

As an example, the economic current range for a 240 mm² conductor will be found. Equations (12) and (13) are used.

$$\text{Lower limit of } I_{max} = \sqrt{\frac{500 \times (52{,}2 - 45{,}96) \times 10^3}{9{,}2341 \times 500 \times (0{,}181 - 0{,}140)}} = 128 \text{ A} \qquad \text{(equation 12)}$$

$$\text{Upper limit of } I_{max} = \sqrt{\frac{500 \times (58{,}99 - 52{,}2) \times 10^3}{9{,}2341 \times 500 \times (0{,}140 - 0{,}114)}} = 168 \text{ A} \qquad \text{(equation 13)}$$

The upper limits of current for a range of standard conductor sizes, when installed under the conditions assumed for this example, have been similarly worked out. Since the lower limit of current for a given size of conductor is also the upper limit for the next smaller conductor, the values calculated can be expressed as current ranges as shown in the following table.

Economic current ranges for cable sizes 25 mm² to 400 mm²

Nominal size mm²	Current range A	
25	–	19
35	19	27
50	27	34
70	34	48
95	48	66
120	66	85
150	85	98
185	98	128
240	128	168
300	168	231
400	231	–

Relationships between maximum load during the first year and total cost per unit length for three sizes of cable are given in figure A.2. It can be seen that each size of cable provides the most economical installation over a range of currents.

The effect of a change in conductor size on the overall costs, when carrying a given load, is shown in figure A.3. Here the cable and financial parameters of this example have been retained, but a fixed load, I_{max}, of 100 A has been assumed. It can be seen that, in the region of the most economic size, the total costs are not greatly affected by the choice of cable size. However, the reduction in costs, compared with those based on the use of a size chosen from thermal considerations, is very significant.

A.3.2 *Selection of an economic conductor size for each section*

From the economic current ranges tabulated in A.3.1 above it is possible to select an appropriate conductor size for each section of the cable route, based on each value of I_{max} for the first year. The sizes so selected for each section are given in table A.2 together with the costs calculated by means of equation (11).

A typical example of the calculation of costs is given below.

For section 1, I_{max} is 160 A.

The economic conductor size selected from the table in A.3.1 is 240 mm², which has an economic current range of 128 A to 168 A.

$$\begin{aligned} CT &= [52{,}2 \times 500] + [160^2 \times (0{,}140/1\,000) \times 500 \times 9{,}2341] \\ &= 26\,100 + 16\,548 \\ &= 42\,648 \text{ cu} \end{aligned}$$

The costs for each section of the route are summarized in table A.2.

It can be seen from table A.2 that the total cost for the cable installation over 30 years on an economic basis is 290 535 cu.

A.3.3 *Conductor size based on maximum load - Choice based on thermal ratings*

The cable size for each section is chosen so as to carry the anticipated maximum load for the last year of the economic life and not to exceed the maximum permissible conductor temperature.

For section 1:

I_{max} (first year) = 160 A

$$\begin{aligned} \text{Maximum current in last year} &= 160 \times [1 + (0{,}5/100)]^{30-1} \\ &= 160 \times 1{,}1556 \\ &= 185 \text{ A} \end{aligned}$$

The required current-carrying capacity (100 % load factor), I, for the final year shall be not less than:

$$185/1{,}11 = 167 \text{ A}$$

where the number 1,11 is the cyclic rating factor assumed in A.2 b) above.

From the following table of current ratings (calculated according to the methods in IEC 287 for this type of cable when installed in the ground) the required conductor size is 70 mm².

Nominal size, mm²	25	35	50	70	95	120	150	185	240	300	400
Current-carrying capacity, A	103	125	147	181	221	255	281	328	382	429	482

In order to make a fair comparison with the losses and financial figures calculated for the economic choice of conductor size, it is necessary to assume an appropriate conductor temperature at which to calculate the losses. For the economic choice it was assumed that the temperature of the conductor would be about 40 °C (see clause 4). It is proposed here that a comparable assumption for the temperature of conductors chosen on the basis of thermal ratings would be the maximum permissible value of 80 °C.

The conductor resistance at a temperature of 80 °C is given in table A.1.

The total cost of section 1 during the 30-year period is obtained from equation (11).

$$\begin{aligned} CT &= [32{,}95 \times 500] + [160^2 \times (0{,}553/1\,000) \times 500 \times 9{,}2341] \\ &= 16\,475 + 65\,363 \\ &= 81\,838 \text{ cu} \end{aligned}$$

Comparison with the cost for this section when using the economical size of conductor, evaluated in A.3.2, shows that the saving in cost for this section is
(81 838-42 648) x 100/81 838 = 48 %.

Similar calculations using sizes based on maximum thermal current-carrying capacity have been made for all the sections and are given in table A.3. The total saving for the ten sections is (547 864 - 290 535) x 100/547 864 = 47 %.

A.4 Calculation using the economic conductor size method (see 5.2)

Route section 1 is used as an example.

I_{max} = 160 A

ρ_{20} = 30,3 x 10^{-9} Ω.m (see 5.2.1)

α_{20} = 0,00403 K^{-1}

B = 1,023 (assuming initially that a conductor size of 185 mm² could be the economic optimum)

A = 0,1133 cu/m.mm² (coefficient of the variable part of the installation costs, see 5.2.2)

$$F = 9{,}2341 \text{ cu/W}$$

$$\theta_m = (80 - 20)/3 + 20 = 40 \text{ °C}$$

$$S_{ec} = 1\,000 \times \left[\frac{160^2 \times 9{,}2341 \times 30{,}3 \times 10^{-9} \times 1{,}023[1 + 0{,}00403(40 - 20)]}{0{,}1133} \right]^{0{,}5}$$

$$= 264 \text{ mm}^2$$

Thus either a 240 mm² or a 300 mm² conductor size could be chosen.

The initial choice of a 185 mm² conductor for the estimation of B can now be improved.

Recalculating with a value of $B = 1{,}057$, for a 300 mm² conductor, gives a value for S_{ec} of 269 mm², which is also within the 240 mm² to 300 mm² range. .

The total cost for each of the possible conductor sizes is now calculated with the aid of equation (11).

$$\begin{aligned} CT_{240} &= [52{,}2 \times 500] + [160^2 \times (0{,}140/1\,000) \times 500 \times 9{,}2341] \\ &= 26\,100 + 16\,548 \\ &= 42\,648 \text{ cu} \end{aligned}$$

$$\begin{aligned} CT_{300} &= [58{,}99 \times 500] + [160^2 \times (0{,}114/1\,000) \times 500 \times 9{,}2341] \\ &= 29\,495 + 13\,474 \\ &= 42\,969 \text{ cu} \end{aligned}$$

The 240 mm² conductor is therefore the more economical size.

Sizes and costs for the other sections have been calculated in a similar manner. The values agree identically with those derived by the previous method demonstrated in A.3.1 and A.3.2 and the summary of sizes and cost is the same as that already given in table A.2.

A.5 Calculation based on the use of one standard conductor size for all sections of the route

A.5.1 *Using the economic current range method*

It is first necessary to assume a probable conductor size and the total cost is calculated with equation (11) using this size for all sections. Then costs assuming the use of the next smaller and larger sizes of conductor are calculated in order to confirm that the assumed size is indeed the most economical.

For the purpose of this example it is assumed that a 185 mm² conductor would be the best choice.

The costs for all sections using 185 mm², and then 150 mm² and 240 mm² have been calculated and are set out in table A.4.

The total costs are:

150 mm²	312 841 cu
185 mm²	312 166 cu
240 mm²	324 707 cu

This indicates that, if for the purpose of standardization one conductor size only can be used, 185 mm² is the most economic choice.

The small change in total cost with change in conductor size noted in A.3.1, and figure A.3, can be seen to apply here also.

A.5.2 *Economic conductor size method*

Although only one conductor size is used, the current is different for each cable section, so that the average losses must be computed (all sections are assumed to operate at the same temperature and hence the same conductor resistance).

$$\frac{\text{Average losses}}{\text{Maximum losses}} = \frac{500 \times 160^2 + 500 \times 144^2 + \ldots + \ldots + 500 \times 16^2}{10 \times 500 \times 160^2}$$

$$= 0{,}385$$

From equation (18), using B for a 185 mm² conductor

$$S_{ec} = 1\,000 \times \left[\frac{160^2 \times 1{,}023 \times 30{,}3 \times 10^{-9}[1 + 0{,}00403(40 - 20)] \times 9{,}2341 \times 0{,}385}{0{,}1133}\right]^{0,5}$$

$$= 164 \text{ mm}^2$$

So that either 150 mm² or 185 mm² conductors could prove to be the most economic.

Total costs for each of these conductors are:

$$CT_{150} = 42{,}00 \times 500 \times 10 + 160^2 \times (0{,}226/1\,000) \times 500 \times 10 \times 9{,}2341 \times 0{,}385$$
$$= 210\,000 + 102\,843$$
$$= 312\,843 \text{ cu}$$

$$CT_{185} = 45{,}96 \times 500 \times 10 + 160^2 \times (0{,}181/1\,000) \times 500 \times 10 \times 9{,}2341 \times 0{,}385$$
$$= 229\,800 + 82\,365$$
$$= 312\,165 \text{ cu}$$

Thus the 185 mm² size is confirmed as the most economic size to use if only one conductor size is to be used throughout the route.

It is clear, by comparison with the sizes chosen in table A.3, that a 185 mm² conductor is thermally adequate to carry the maximum load at the end of the 30-year period.

A.6 Summary of results

A summary of the results of the calculations for the cable and conditions described in A.2 is given below.

Summary of costs

Basis of costing	*CI* cu	*CJ* cu	TOTAL cu	 %
Thermal current-carrying capacity for each section	146 330	401 534	547 864	100
Economic size for each section	202 095	88 440	290 535	53
Economic size using one standard size of 185 mm² throughout	229 800	82 365	312 165	57

Table A.1 – Cable details

Cable size	Resistance by phase at		Primary cost		
mm² (1)	40 °C Ω/km (2)	80 °C Ω/km (3)	Cable cu/m (4)	Laying cu/m (5)	Sum cu/m (6)
25	1,298	1,491	10,62	17,23	27,85
35	0,939	1,079	11,65	17,33	28,98
50	0,694	0,798	13,19	17,49	30,68
70	0,481	0,553	15,24	17,71	32,95
95	0,348	0,400	17,81	17,97	35,78
120	0,277	0,318	20,37	18,24	38,61
150	0,226	0,259	23,45	18,55	42,00
185	0,181	0,208	27,04	18,92	45,96
240	0,140	0,161	32,69	19,51	52,20
300	0,114	0,131	38,85	20,14	58,99
400	0,091	0,104	49,11	21,20	70,31

Table A.2 – Economic loading

Section number		1	2	3	4	5	6	7	8	9	10	
Load												
I_{max}	(A)	160	144	128	112	96	80	64	48	32	16	
Cable												
Size	(mm²)	240	240	185	185	150	120	95	70	50	25	
Capacity	(A)	382	382	328	328	281	255	221	181	147	103	
Costs per section and total												*Sum*
Cable	(cu)	16 345	16 345	13 520	13 520	11 725	10 185	8 905	7 620	6 595	5 310	110 070
Laying	(cu)	9 755	9 755	9 460	9 460	9 275	9 120	8 985	8 855	8 745	8 615	92 025
CI	(cu)	26 100	26 100	22 980	22 980	21 000	19 305	17 890	16 475	15 340	13 925	202 095
CJ	(cu)	16 548	13 403	13 692	10 483	9 616	8 185	6 581	5 117	3 281	1 534	88 440
CT	(cu)	42 648	39 503	36 672	33 463	30 616	27 490	24 471	21 592	18 621	15 459	290 535

Table A.3 - Current-carrying capacity criterion

Section number		1	2	3	4	5	6	7	8	9	10	
Load												
I_{max}	(A)	160	144	128	112	96	80	64	48	32	16	
I_{end}	(A)	185	166	148	129	111	92	74	55	37	18	
$I_{end}/1{,}11$	(A)	167	150	133	117	100	83	67	50	33	17	
Cable												
Size	(mm²)	70	70	50	35	25	25	25	25	25	25	
Capacity	(A)	181	181	147	125	103	103	103	103	103	103	
Costs per section and total												*Sum*
Cable	(cu)	7 620	7 620	6 595	5 825	5 310	5 310	5 310	5 310	5 310	5 310	59 520
Laying	(cu)	8 855	8 855	8 745	8 665	8 615	8 615	8 615	8 615	8 615	8 615	86 810
CI	(cu)	16 475	16 475	15 340	14 490	13 925	13 925	13 925	13 925	13 925	13 925	146 330
CJ	(cu)	65 363	52 944	60 365	62 492	63 443	44 058	28 197	15 861	7 049	1 762	401 534
CT	(cu)	81 838	69 419	75 705	76 982	77 368	57 983	42 122	29 786	20 974	15 687	547 864

Table A.4 - Economic loading, standard conductor size for all sections

Standard size: 150 mm²

Section number		1	2	3	4	5	6	7	8	9	10	
I_{max}	(A)	160	144	128	112	96	80	64	48	32	16	
Cable												
Size	(mm²)	150	150	150	150	150	150	150	150	150	150	
Capacity	(A)	281	281	281	281	281	281	281	281	281	281	
Costs per section and total												*Sum*
Cable	(cu)	11 725	11 725	11 725	11 725	11 725	11 725	11 725	11 725	11 725	11 725	117 250
Laying	(cu)	9 275	9 275	9 275	9 275	9 275	9 275	9 275	9 275	9 275	9 275	92 750
CI	(cu)	21 000	21 000	21 000	21 000	21 000	21 000	21 000	21 000	21 000	21 000	210 000
CJ	(cu)	26 712	21 637	17 096	13 089	9 616	6 678	4 274	2 404	1 068	267	102 841
CT	(cu)	47 712	42 637	38 096	34 089	30 616	27 678	25 274	23 404	22 068	21 267	312 841

Standard size: 185 mm²

Section number		1	2	3	4	5	6	7	8	9	10	
I_{max}	(A)	160	144	128	112	96	80	64	48	32	16	
Cable												
Size	(mm²)	185	185	185	185	185	185	185	185	185	185	
Capacity	(A)	328	328	328	328	328	328	328	328	328	328	
Costs per section and total												*Sum*
Cable	(cu)	13 520	13 520	13 520	13 520	13 520	13 520	13 520	13 520	13 520	13 520	135 200
Laying	(cu)	9 460	9 460	9 460	9 460	9 460	9 460	9 460	9 460	9 460	9 460	94 600
CI	(cu)	22 980	22 980	22 980	22 980	22 980	22 980	22 980	22 980	22 980	22 980	229 800
CJ	(cu)	21 393	17 329	13 692	10 483	7 702	5 348	3 423	1 925	856	214	82 365
CT	(cu)	44 373	40 309	36 672	33 463	30 682	28 328	26 403	24 905	23 836	23 194	312 165

Standard size: 240 mm²

Section number		1	2	3	4	5	6	7	8	9	10	
I_{max}	(A)	160	144	128	112	96	80	64	48	32	16	
Cable												
Size	(mm²)	240	240	240	240	240	240	240	240	240	240	
Capacity	(A)	382	382	382	382	382	382	382	382	382	382	
Costs per section and total												*Sum*
Cable	(cu)	16 345	16 345	16 345	16 345	16 345	16 345	16 345	16 345	16 345	16 345	163 450
Laying	(cu)	9 755	9 755	9 755	9 755	9 755	9 755	9 755	9 755	9 755	9 755	97 550
CI	(cu)	26 100	26 100	26 100	26 100	26 100	26 100	26 100	26 100	26 100	26 100	261 000
CJ	(cu)	16 548	13 403	10 590	8 108	5 957	4 137	2 648	1 489	662	165	63 707
CT	(cu)	42 648	39 503	36 690	34 208	32 057	30 237	28 748	27 589	26 762	26 265	324 707

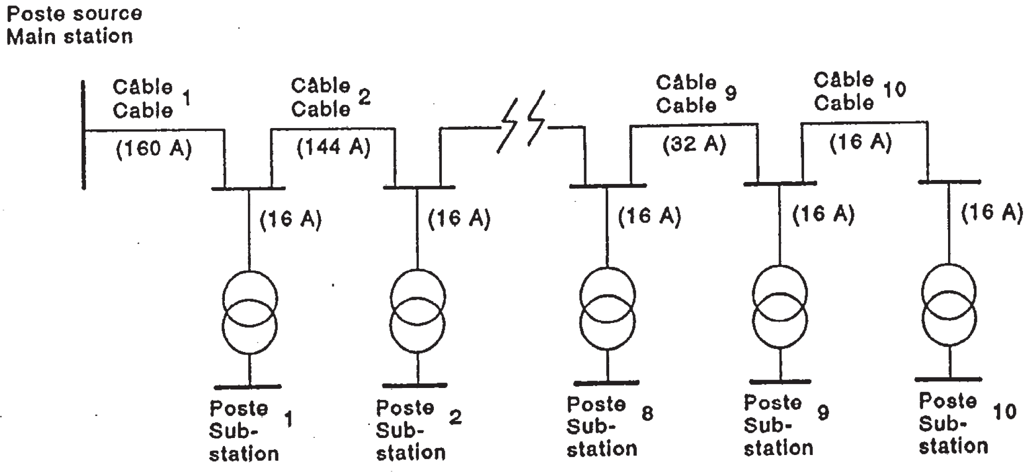

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Figure A.1 – Disposition de la liaison
System layout

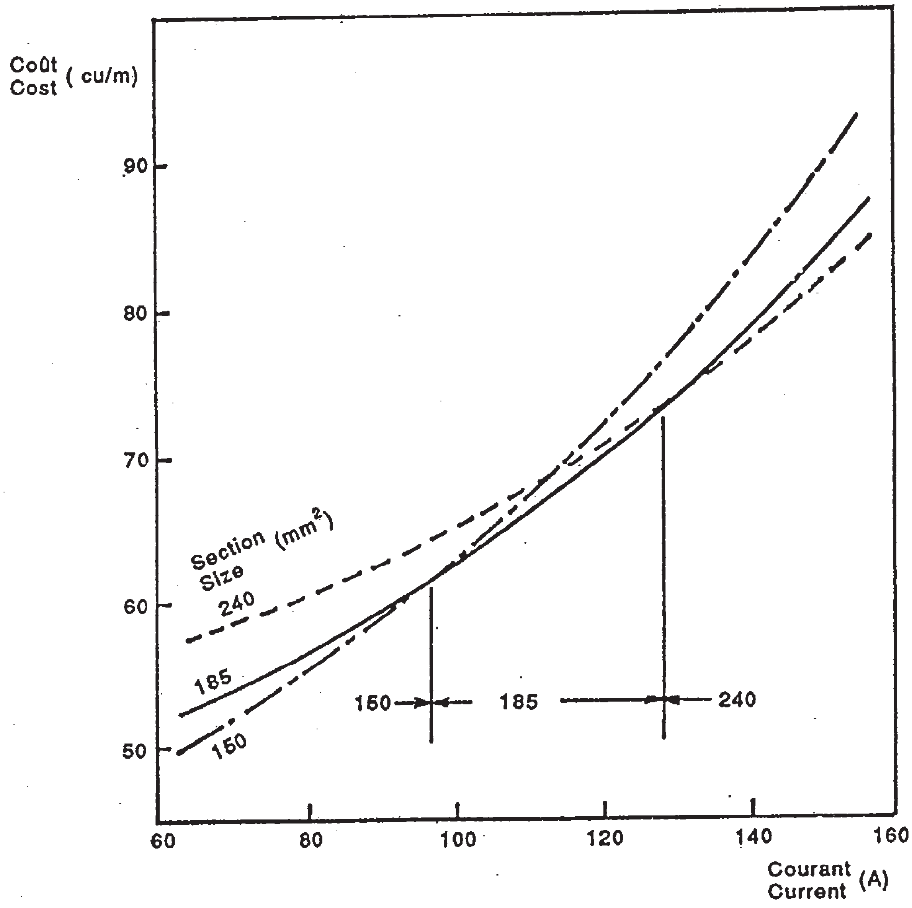

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Figure A.2 – Fourchettes de courant économique
Economic current ranges

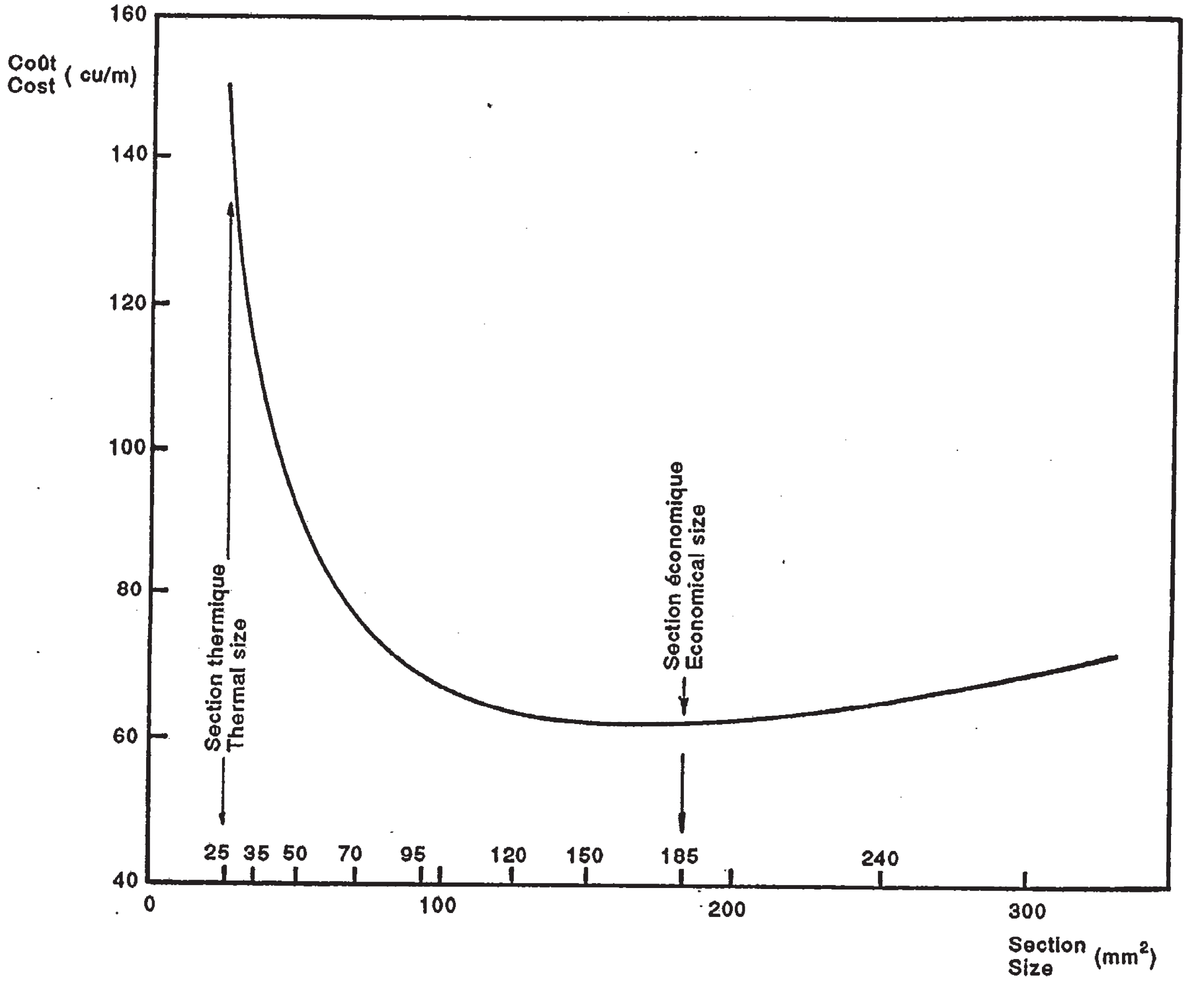

Figure A.3 – Variation du coût en fonction de la section d'âme
Variation of cost with conductor size

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Annex B
(informative)

Mean conductor temperature and resistance

B.1 Methods for estimating mean conductor temperature and resistance

It is convenient and usually sufficiently accurate to assume that conductor resistance is constant during the life of the cable. A simple formula for making an estimate of conductor operating temperature and hence its resistance is given in clause 4. This is based on observations of typical calculations that the average operating temperature rise of an economic size of conductor, taken over its economic life, is in the region of one third of the rise occurring with its maximum permissible thermal rating.

For the example used in this standard, errors in conductor size and total costs, as a result of using this estimate, are not greater than about 2 %. However, larger errors may occur where the combination of installed cost, cost of losses and load growth lead to conductor temperatures, during the final years of the economic period, approaching the maximum permissible value.

In general, a more precise value of conductor resistance will affect the selection of an economic size only in very marginal cases. There may be situations where better precision in the cost of energy losses is required and the additional effort can be accepted.

If greater accuracy is desired for particular cases, refined values for conductor temperature and resistance can be made, using as a starting point the conductor size or range of economic currents obtained by means of the simple temperature estimate suggested in clause 4.

B.2 Formulae to determine mean conductor temperature and resistance

Conductor temperature, as a mean of the values during the first and last years of an economic period, can be obtained from:

$$\theta_m = \frac{\theta_s + \theta_f}{2} = \frac{\beta + \theta_a}{2}\left[\frac{1}{1-\gamma} + \frac{1}{1-g\gamma}\right] - \beta \ (^\circ\mathrm{C}) \qquad (19)$$

where

θ_s = conductor temperature during the first year, °C;
θ_f = conductor temperature during the last year, °C;
θ_a = ambient temperature, °C;
β = reciprocal of the temperature coefficient of resistance of the conductor material, K.

For aluminium $\beta = 228$, for copper $\beta = 234{,}4$;

$$\gamma = \left[\frac{I_{max}}{I_z}\right]^2 \left[\frac{\theta - \theta_a}{\beta + \theta}\right] \qquad (20)$$

I_{max} = value of load current during the first year, A;
I_z = current-carrying capacity, for a maximum permitted temperature rise of $\theta - \theta_a$, using IEC 287, A;
θ = maximum permissible conductor temperature, °C;
g = $(1 + a/100)^{2(N-1)}$;
a = annual increase in I_{max}, %;
N = duration of economic period, years.

The mean conductor resistance, as an average of the values during the first and last years is:

$$R_m = \frac{R_{20}}{2} \left(\frac{\beta + \theta_a}{\beta + 20}\right) \left(\frac{1}{1 - \gamma} + \frac{1}{1 - g\gamma}\right) \quad (\Omega/\text{m}) \qquad (21)$$

The value of R_m can be substituted directly in equations (11), (12) and (13).

Similarly, the following equation can be used to obtain a value of ρ_m which can be substituted for $\rho_{20}[1 + \alpha_{20}(\theta_m - 20)]$ in equations (15) and (18):

$$\rho_m = \frac{\rho_{20}}{2} \left[\frac{\beta + \theta_a}{\beta + 20}\right] \left[\frac{1}{1 - \gamma} + \frac{1}{1 - g\gamma}\right] \quad (\Omega.\text{m}) \qquad (22)$$

B.3 Application to the determination of an economic current range (see 5.1)

This application is based on the example in A.3 of annex A.

Consider the current range calculated for a 240 mm² conductor and let $I(1)$ and $I(2)$ be the lower and upper limits to this range, calculated by means of the simple estimate of conductor temperature. In the example, $I(1)$ = 128 A and $I(2)$ = 168 A.

The following data are needed for the three conductor sizes involved:

Size mm²	R_{20} Ω/km	C_l cu/m	I_z A *	$I_{max.z}$ $= I_z \times M$, A **
185	0,1675	45,96	328	364
240	0,1296	52,20	382	424
300	0,1053	58,99	429	476

* See A.3.3 of annex A.
** The cyclic rating factor M = 1,11, see A.2 of annex A.

From A.2:

$$F = 9{,}2341.$$

The procedure for re-estimating the operating temperature and conductor resistance for the upper limit of the current range for the 240 mm² conductor is as follows.

Calculate the auxiliary quantity γ, from

$$\gamma(240) = \left(\frac{168}{424}\right)^2 \times \left(\frac{80-20}{228+80}\right) = 0{,}03058 \qquad \text{(equation (20))}$$

where the value of 168 A was derived by the initial calculation in A.3 using the simple estimate for θ_m.

The increase in power loss due to growth in load is

$$g = [1 + (a/100)]^{2(N-1)}$$
$$= 1{,}3355$$

hence $g\gamma(240) = 1{,}3355 \times 0{,}03058 = 0{,}04084$.

Then the improved estimate for the resistance of the 240 mm² conductor is obtained from:

$$R_m(240) = \left(\frac{0{,}1296}{2}\right) \times \left(\frac{228+20}{228+20}\right) \times \left(\frac{1}{1-0{,}03058} + \frac{1}{1-0{,}04084}\right)$$
$$= 0{,}1344\ \Omega/\text{km}. \qquad \text{(equation (21))}$$

Similarly, for the 300 mm² conductor,

$$\gamma(300) = \left(\frac{168}{476}\right)^2 \times \left(\frac{80-20}{228+80}\right) = 0{,}02427 \qquad \text{(equation (20))}$$

and $g\gamma(300) = 1{,}3355 \times 0{,}02427 = 0{,}03241$

then,

$$R_m(300) = \left(\frac{0{,}1053}{2}\right) \times \left(\frac{228+20}{228+20}\right) \times \left(\frac{1}{1-0{,}02427} + \frac{1}{1-0{,}03241}\right)$$
$$= 0{,}1084\ \Omega/\text{km}. \qquad \text{(equation (21))}$$

The revised upper current limit is then:

$$I(2) = \sqrt{\frac{500 \times (58{,}99 - 52{,}20) \times 1\,000}{9{,}2341 \times 500 \times (0{,}1344 - 0{,}1084)}} \qquad \text{(equation 12)}$$
$$= 168\ \text{A}.$$

The difference from the initial value of 168 A is within errors due to rounding and because temperatures of both conductors have been corrected by about the same amount. The selection of a 240 mm² conductor for a maximum load of 160 A for the first section of the cable route is not affected.

A similar calculation can be made for the lower limit.

The total cost, *CT*, obtained by the initial calculation was 42 648 cu (see A.3.2); a cost based on the refined value of resistance for the 240 mm² conductor can now be obtained.

At the value of maximum load current, I_{max} = 160 A, the auxiliary quantity is:

$$\gamma(240) = \left(\frac{160}{424}\right)^2 \times \left(\frac{80 - 20}{228 + 80}\right) = 0{,}02774 \qquad \text{(equation (20))}$$

$$g\gamma(240) = 1{,}3355 \times 0{,}02774 = 0{,}03705$$

so that:

$$R_m(240) = \left(\frac{0{,}1296}{2}\right) \times \left(\frac{228 + 20}{228 + 20}\right) \times \left(\frac{1}{1 - 0{,}02774} + \frac{1}{1 - 0{,}03705}\right)$$

$$= 0{,}1339\ \Omega/\text{km} \qquad \text{(equation (21))}$$

$$CT = 52{,}2 \times 500 + 160^2 \times \frac{0{,}1339}{1\,000} \times 9{,}2341 \times 500 \qquad \text{(equation (11))}$$

$$= 26\,100 + 15\,827$$

$$= 41\,927 \text{ cu}$$

When compared with the cost of 42 648 cu obtained for this example by the simpler procedure, the reduction can be seen to be less than 2 %.

B.4 Application to the determination of an economic size of conductor (see 5.2)

Numerical values for this explanation are taken from the example in A.4.

The example in A.4, after correction for the a.c. resistance factor *B*, showed the most economical cross-section as 269 mm², which is marginally closer to the standard size of 240 mm² than to the 300 mm² size.

A re-assessment of this size, making a correction to the conductor resistance, can now be made. The relevant data for a 240 mm² conductor is already given in B.2. The load to be carried is 160 A.

$$\gamma(240) = \left(\frac{160}{424}\right)^2 \times \left(\frac{80 - 20}{228 + 80}\right) = 0{,}02774 \qquad \text{(equation (20))}$$

$$g\gamma(240) = 1{,}3355 \times 0{,}02774 = 0{,}03705$$

The new value of resistivity, corrected for temperature, is given by:

$$\rho_m = \frac{30{,}3 \times 10^{-9}}{2} \times \left(\frac{228 + 20}{228 + 20}\right) \times \left(\frac{1}{1 - 0{,}02774} + \frac{1}{1 - 0{,}03705}\right)$$

$$= 30{,}3 \times 10^{-9} \times 1{,}0335 \qquad \text{(equation (22))}$$

$$= 31{,}32 \times 10^{-9}\ \Omega.\text{m}$$

and the most economic size is:

$$S_{ec} = 1\,000 \times \left[\frac{160^2 \times 9{,}2341 \times 31{,}32 \times 10^{-9} \times 1{,}057}{0{,}1133}\right]^{0{,}5} \qquad \text{(equation (18))}$$

$$= 263\ \text{mm}^2$$

This trivial change brings S_{ec} a little closer to the standard value of 240 mm².

The total cost for a 240 mm² conductor cable will be the same as that already calculated in B.2.

The mean temperature of the 240 mm² conductor during the economic life is:

$$\theta_m = \left(\frac{228 + 20}{2}\right) \times \left(\frac{1}{1 - 0{,}02774} + \frac{1}{1 - 0{,}03705}\right) - 228 \qquad \text{(equation (19))}$$

$$= 28{,}3\ ^\circ\text{C}.$$

Publication(s) referred to

See national foreword.

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