TECHNOLOGY

BEHIND

ELECT

A

COMPUTER PROGRAM

ON

CABLES & OVERHEAD LINES

WITH SPECIFIC AND WIDE COVERGAE ON ENERGY AUDIT

&

SAG-TENSION IN OVERHEAD LINES

December 2005

By:
Mohammed Zahoor Ali

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PREFACE

Cables and overhead lines are integral part of any Electrical system or network. Larger the network, greater is the complexity. The ***ELECT*** computer program has been prepared to solve the complex conditions by feeding minimum possible information. This part of the program deals with Overhead Lines, Cables and Transformers. Although, each of these has a vast technology, it has been tried to arrive at more accurate results by using more practicable solutions.

The latest version of this Software has included the following:

1. Cost estimate of Overhead Lines
2. Energy Bill Analysis with graphical display
3. Cost estimate of different type and grade of Power Cables.
4. Back-up calculations of Sag/Tension, Energy Bill verification and Percentage Impedance of Transformers.
5. Technology behind Elect in PDF format

This ***ELECT*** software may be divided in the following three categories:

1. Software part
2. User's Manual part
3. Technology part

Software part is the main computer program prepared in high-level languages and is very much user friendly. However, it is essential to understand the aims and objectives of this software before use.

User's Manual is in the form of a booklet. This manual is also provided in PDF Format, along-with this software, so that any number of copies can be reproduced if necessary.

Technology part as mentioned above at (5) is now being supplied with this software in PDF format.

Readers and Users may like to send their healthy suggestions, if any, for improvement of this program. They will be cordially accepted with thanks and shall be tried to incorporate in its future versions.

Readers of this book and users of the *ELECT* software may feel free to email their comments directly to the authors.

Bhubaneswar — Authors
15th January 2005 — sofexindia@yahoo.com

INTRODUCTION

Energy conservation can be considered as an alternate source of energy. The cost of supplying incremental energy is far less if it is made up by implementing energy conservation measures as against the investment required to create equivalent resources. The expert committee, constituted by Government of India, has suggested all large and medium sized industries:

1. To carry out detailed energy audits.
2. To improve the efficiency of utilisation.
3. To appoint energy managers as a mandatory measure.
4. To use energy efficient equipment.
5. To review and identify the R&D efforts required to reduce energy consumption for every major industrial process.
6. To organise formal training courses for developing energy conservation expertise.
7. To form a system of government recognition and awards for honouring individuals and organisations for outstanding performances in energy conservation.

The above is a list of few extracted measures of the expert committee on energy, which speaks of itself about the importance of energy conservation. In view of the experts committee’s recommendations, the importance of the *ELECT* software has increased.

Moreover, the *ELECT* Software Version-7 has included the following topics to make it more suitable for practical utilisation:

1. Conductor cost index (area index) has been revised and made upto-date and is now suitable for use in any country/ currency.
2. Overhead Line costing with different possible specifications.
3. Default data set has been included as per Indian standards.
4. Voltage regulation/ drop, losses etc. now can be found for single as well bundled conductors/cables with same or unequal sizes.
5. Graphical illustration of the most economical conductor selection.
6. Complete energy audit reports of overhead lines at fingertips.
7. Attractive get up and user-friendly presentation.
8. A complete and exhaustive programme on Sag and Tension of overhead lines with facility to view each and every calculation.
9. Complete technology behind the *ELECT* software in pdf format.
10. A complete & separate program on Cable Properties, Cable Selection and Regulation/ Voltage Drop/ Losses in single or bundled cables.
11. Cable Selection, load analysis & costing
12. Transformer Selection, pf improvement, power balance etc.

ABOUT ENERGY AUDIT

In a developing country, like ours, the demand of energy is continuously growing at a higher rate than normal, widening the gap between demand and supply. Bridging this gap is a costly affair.

For most of the industries, the share of energy cost in the total production cost is quite significant. Reduction of energy cost can improve profit levels in such cases. The reduction can be achieved by improving the efficiency of industrial operations and equipment.

Energy audits play an important role in identifying energy conservation opportunities in the industrial sector. While they do not provide the final answer to the problem, they do help to identify the existing potential for energy conservation, and induces the companies to concentrate their efforts in this area in a focussed manner.

The cost of domestic as well as commercial energy is very high compared to many other countries of the world. With the fact that conservation of energy will grow at a robust pace with the increased level of economic activity, the cost of energy production and consumption would become much higher in future.

The industries sector alone consumes about 50% of the total commercial energy, while it contributes only about 25% of the country's GDP.

Several efforts at analysing the potentials of energy savings in the industrial sector indicate a range of 20% - 25% reduction without significant investments.

For any industrial unit, the first step in adopting a plan for improvement of energy efficiency is to carry out an energy audit. Energy audit provides a quantitative and technical base for assessing how different forms of energy are being used and for quantifying energy used according to discrete functions. They are important tools for identifying the potentials for improvements in the energy efficiencies, and indicate direction towards on which energy management efforts should be concentrated.

ELECTRICAL ENERGY

This book has covered the technology used behind the electrical energy audit software *ELECT*. The *ELECT* software deals with the engineering of overhead transmission lines and cables, with specific stress on energy audit aspects. The purpose of the *ELECT* software is to provide a technical platform for finding suitable, most economical, technically feasible, standard and easily available conductor or cable for an electrical system with due consideration of the system stability and other relevant technical requirements. The *ELECT* software is very much useful for in-depth audit of energy transmission and distribution through an overhead line or cable.

Energy audit of a system can be categorised as under:

1. Transmission & Distribution System e.g. Overhead lines, cables, transformers etc.
2. Mechanical System performing a job e.g. motors, pumps, transport etc.

A number of losses/ wastages occur between the point of generation of electrical energy and its actual consumption in performing a job. The purpose of energy audit is to check for the losses and wastages of electrical energy flow system. This boo has restricted discussion on Transmission and Distribution network only.

DISTRIBUTION SYSTEMS OF ELECTRICAL ENERGY

Distribution network for the electrical energy is normally done through the following two systems:

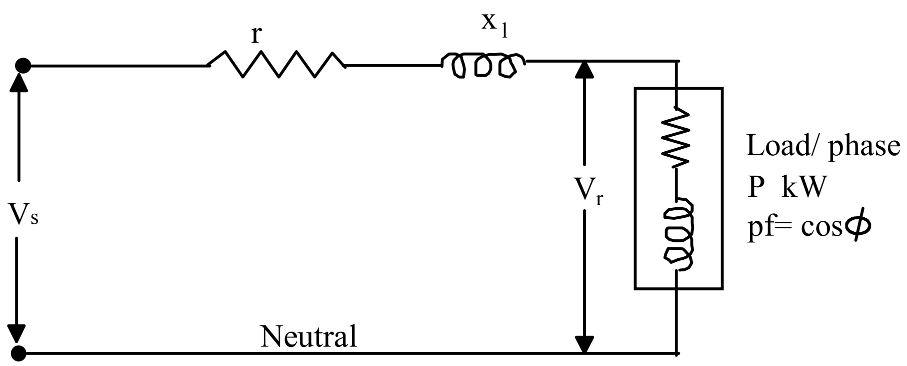
1. Overhead transmission line network system
2. Cable network system

In overhead line system, two types of situation may arise. Firstly, when the 'Sending End voltage is known' and secondly, when the 'Receiving end voltage' is known. Both these aspects of the overhead lines are discussed hereunder.

However, it is to be noted here that the effect of line capacitance has only been taken in the second case, i.e. when 'Receiving end voltage is known'.

VOLTAGE DROP AND PERCENTAGE REGULATION IN OVERHEAD LINES

CASE(1): ***WHEN SENDING END VOLTAGE IS KNOWN***



Let Power factor= cosΦ
Total length of line = l (in km)
Spacing between conductors = d (in mm)
Radius of the conductor = R (in mm)

Reactance of the line per phase per km is given by (Refer to page-28):

$$x_l = \frac{\pi}{100}\left[0.5 + 2.\ln\left(\frac{d}{R}\right)\right]$$ Ω/km Note: d and R are in the same unit

=> This can also be found from Tables because inductance is given by:

$$L = \left[0.5 + 2.\ln\left(\frac{d}{R}\right)\right]$$ Henry/m

Capacitance of the line per phase/ km is given by:

$$C = \frac{2\pi K_0}{\ln\left(\frac{d}{R}\right)} \qquad \left[\text{Where } K_0 = \frac{10^{-9}}{36\pi}\right.$$

$$= \frac{2\pi \times \frac{10^{-9}}{36\pi}}{\ln\left(\frac{d}{R}\right)} \text{ Farad/ m}$$

$$= \frac{10^{-3}}{18.\ln\left(\frac{d}{R}\right)} \mu F/km$$

$$C = \frac{1}{18.\ln\left(\frac{d}{R}\right)} \mu F/km$$

Resistance of the overhead line/ phase/ km can be found from Tables, alternatively, it can be assessed from the following formula:

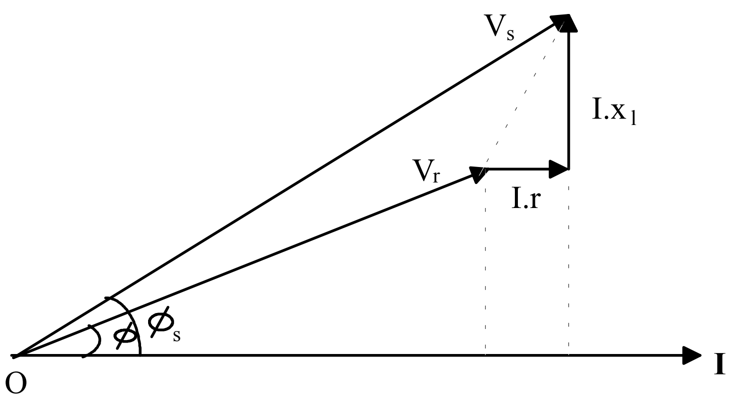
$$r = \rho\frac{l}{a} = 17.86 \times \frac{l}{a}$$

Where l is in km,

a in sq.mm.(equivalent Cu) and,

ρ=Sp. resistance of copper

$= 17.86 \ \ \Omega mm^2/km$



Let r, x_l and C be the total resistance, inductive reactance and capacitance of l km long overhead line per phase respectively. V_s and V_r be the sending end and receiving end phase voltages respectively. I be the load current, Φ be the load power factor and Φ_s be the sending end power factor. Then the vector diagram of the system is as shown in the above figure.

$P = \frac{V_r.I.\cos\Phi}{1000}$ => Active power per phase

$Q = \frac{V_r.I.\sin\Phi}{1000}$ => Reactive power per phase

$V_s^2 = (V_r \cos\Phi + I.r)^2 + (V_r.\sin\Phi + I.x_l)^2$

$= V_r^2 \cos^2\Phi + I^2.r^2 + 2V_r I.r.\cos\Phi + V_r^2 \sin^2\Phi + I^2.x_l^2 + 2V_r I.x_l.\sin\Phi$

$= V_r^2 + I^2.(r^2 + x_l^2) + 2.r.1000.P + 2.x_l.1000.Q$

$= V_r^2 + 2000(P.r + Q.x_l) + I^2.Z^2$ [Where $Z^2 = r^2 + x_l^2$

But, $I = \dfrac{1000 \times P}{V_r.\cos\Phi}$

Therefore, $V_s^2 = V_r^2 + 2000.(P.r + Q.x_l) + \dfrac{P^2.Z^2 \times 10^6}{\cos^2\Phi.V_r^2}$

Or, $V_r^4 - V_r^2[V_s^2 - 2000.(P.r + Q.x_l)] + \dfrac{P^2.Z^2 \times 10^6}{\cos^2\Phi.V_r^2} = 0$

This is a quadratic equation in V_r , to find the roots of the equation the following method is being used:

Let $AA = V_s^2 - 2000.(P.r + Q.x_l)$ $B = \dfrac{P^2.Z^2 \times 10^6}{\cos^2\Phi.V_r^2}$,

The above equation reduces to:

$$V_r^4 - V_r^2.AA + B = 0$$

Therefore, $V_r^2 = \dfrac{AA \pm \sqrt{AA^2 - 4B}}{2}$

So, $V_r = \sqrt{\dfrac{AA \pm \sqrt{AA^2 - 4.B}}{2}}$

Also from the vector diagram:

$\cos\Phi_s = \dfrac{V_r \cos\Phi + I.r}{V_s}$ and, Regulation $= \dfrac{V_s - V_r}{V_s} \times 100$

Line efficiency is given by:

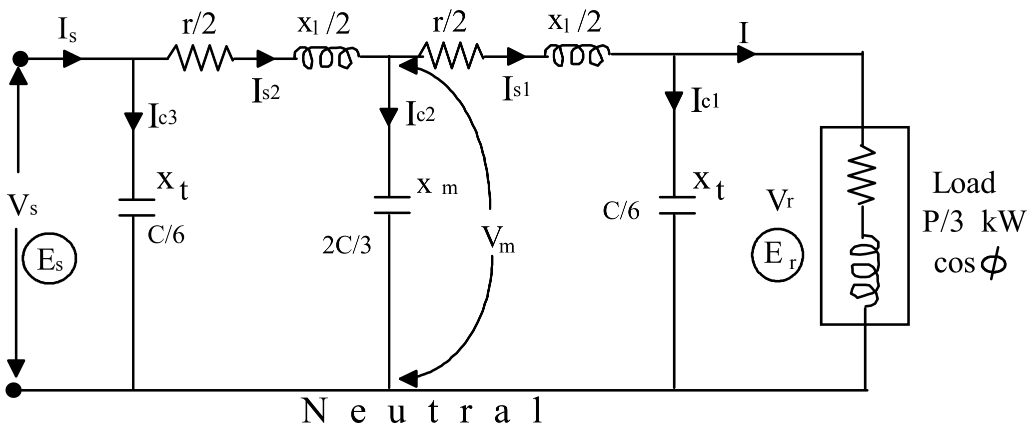
$$\eta = \frac{Output\_power\_per\_phase}{Output\_power\_per\_phase) + \frac{1}{3} \times Total\_losses} \times 100$$

Voltage drop = $V_s - V_r$

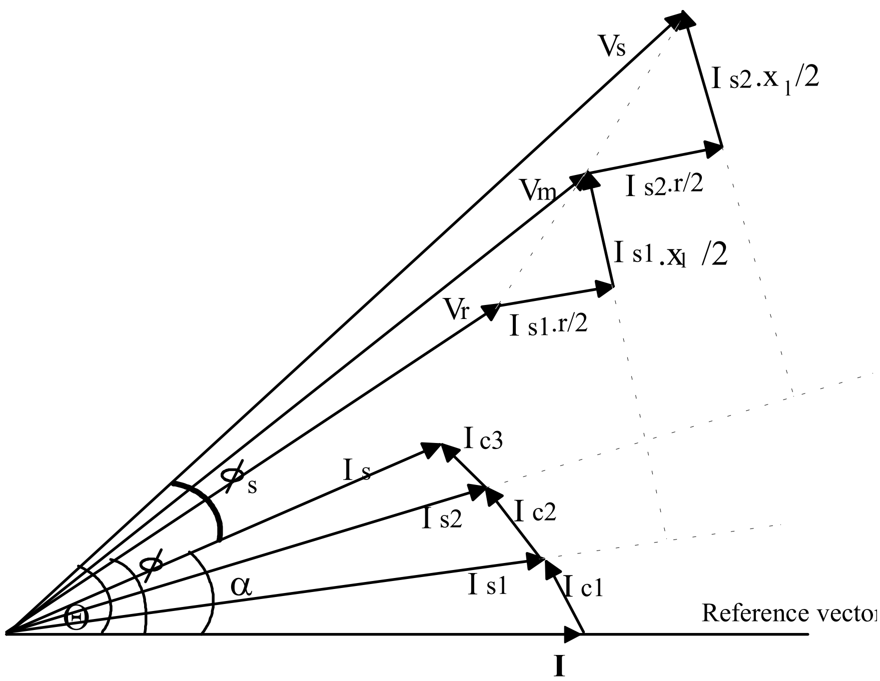
$Surge\_impedance = \dfrac{V_s}{I_s}$ (In open circuit condition)

$$= \sqrt{\frac{L}{C}} \quad \Omega$$

CASE(2): ***WHEN RECEIVING END VOLTAGE IS KNOWN***



Let Load current= I amp.
Power factor = $\cos\Phi$
Resistance per phase per km = r Ω
Inductive reactance per phase per km = x_l Ω
Capacitance per phase per km = C Farad,
V_r = Receiving end voltage per phase,
P = 3 phase Load in kW,
I_{c1} , I_{c2} , I_{c3} , I_s , I_{s1} and I_{s2} are the currents in amps. as shown in the above circuit diagram.



Given conditions are:

Length of overhead line = 1 km.
Receiving end voltage = V_r

Resistance of the OHL per phase per km in Ω
Inductive reactance of the OHL per phase per km in Ω
Capacitance of the OHL per phase per km in Farad
3 phase load = P kW
Power factor of the load = cosΦ

To find out the following:
Sending end Voltage V_s
Sending end current I_s
Sending end power factor cosΦ
Efficiency of the line η
Total line losses
Line voltage regulation.

Let r, x_l and C be the total resistance, inductive reactance and capacitance of l km long overhead line per phase.

Then, $x_l = \dfrac{1}{\omega \dfrac{C}{6}} = \dfrac{6}{\omega C}$ and $x_m = \dfrac{1}{\omega . \dfrac{2C}{3}} = \dfrac{3}{2\omega C}$,

Resistance r, reactance x_l and capacitance C can be obtained from tables:
Reference vector I can be found from the following equation:

$$\hat{I} = \frac{P}{3.V_r.\cos\Phi} = \mathrm{I} + \mathrm{j}.0$$

$$\hat{V}_r = V_r(\cos\Phi + j.\sin\Phi)$$

$$= V_x + j.V_y \qquad \text{(Say)}$$

$$\hat{I}_{c1} = \frac{\hat{V}_r}{-j.x_l} = \frac{\hat{V}_r.\omega.C}{-j.6},$$

$$= j.\left(\frac{\hat{V}_r.\omega.C}{6}\right) = j.\frac{\hat{V}_r}{x_l}.$$

Now, $\hat{I}_{s1} = \hat{I} + \hat{I}_{c1}$

$$\hat{I}_{s1} = (I + j.0) + \left(0 + j.\frac{\hat{V}_r}{x_l}\right),$$

or $\hat{I}_{s1} = \mathrm{I}_x + \mathrm{j}.\ \mathrm{I}_y$ (Say)

Voltage drop in the receiving half line

$$= \hat{I}_{s1}\left(\frac{r}{2} + j.\frac{x_l}{2}\right) = \left(I_x + j.I_y\right)\left(\frac{r}{2} + j.\frac{x_l}{2}\right)$$

$$= V_{x1} + j.V_{y1}$$

Mid line voltage is given by:

$$\hat{V}_m = \hat{V}_r + drop\_in\_receiving\_half\_line$$

$$= \left(V_x + j.V_y\right) + \left(V_{x1} + j.V_{y1}\right)$$

Hence, $\hat{V}_m = \left(V_x + j.V_y\right) + \left(V_{x1} + j.V_{y1}\right)$

Also,
$$\hat{I}_{c2} = \frac{\hat{V}_m}{-j.x_m} = j.\frac{\hat{V}_m}{x_m}$$
$$= \frac{j}{x_m}\left[\left(\left(V_x + V_{x1}\right) + j.\left(V_y + V_{y1}\right)\right)\right]$$
$$= -\frac{V_y + V_{y1}}{x_m} + j\frac{V_x + V_{x1}}{x_m}$$

Now,
$$\hat{I}_{s2} = \hat{I}_{s1} + \hat{I}_{c2}$$
$$= (I_x + j.I_y) + \left(-\frac{V_y + V_{y1}}{x_m} + j.\frac{V_x + V_{x1}}{x_m}\right)$$
$$= I'_x + jI'_y$$

Voltage drop in the sending half of the line is given by:
$$= \hat{I}_{s2}.\left(\frac{r}{2} + j\frac{x_l}{2}\right) = \left(I'_x + j.I'_y\right)\left(\frac{r}{2} + j.\frac{x_l}{2}\right)$$
$$= V_{x2} + j.V_{y2}$$

Sending end voltage is thus given by:
$$\hat{V}_s = \hat{V}_m + drop\_in\_sending\_half\_line$$
$$= \left(V_x + V_{x1}\right) + j.\left(V_y + V_{y1}\right) + V_{x2} + j.V_{y2}$$
$$= \left(V_x + V_{x1} + V_{x2}\right) + j.\left(V_y + V_{y1} + V_{y2}\right)$$

Sending end Power factor angle:

$$\Phi_s = \theta - \alpha$$ [From vector diagram

$$\theta = \tan^{-1}\left(\frac{V_y + V_{y1} + V_{y2}}{V_x + V_{x1} + V_{x2}}\right)$$ [From V_s

α = Angle between I_s and I

Sending end current is given by:

$$\hat{I}_s = \hat{I}_{s2} + \hat{I}_{c3}$$
$$\hat{I}_{c3} = \frac{\hat{V}_s}{-j.x_t} = j.\frac{\hat{V}_s}{x_t} = \frac{j}{x_t}\left[\left(V_x + V_{x1} + V_{x2}\right) + j\left(V_y + V_{y1} + V_{y2}\right)\right]$$
$$\hat{I}_{c3} = \frac{V_y + V_{y1} + V_{y2}}{x_t} + j.\frac{V_x + V_{x1} + V_{x2}}{x_t}$$

Now, $I_s = I_{s2} + I_{c3}$

$$= \left(I'_x + j.I'_y\right) + \left(-\frac{V_y + V_{y1} + V_{y2}}{x_t} + j.\frac{V_x + V_{x1} + V_{x2}}{x_t}\right)$$

Or $I_s = I''_x + j.I''_y$

Therefore, $\alpha = \tan^{-1}\left(\frac{I''_y}{I''_x}\right)$

Also, $\Phi_s = \theta - \alpha$

Thus, sending end power factor is given by:

$$\cos\Phi_s = \cos(\theta - \alpha)$$

Now, Voltage available at receiving end = V_r (Phase voltage)

$= \sqrt{3}.V_r$ (Line voltage)

Sending end voltage = V_s (Phase voltage)

$= \sqrt{3}.V_s$ (Line voltage)

Percentage regulation = $\frac{|V_s| - |V_r|}{|V_s|} \times 100$

Line efficiency:

Line input power = $3.V_s.I_s.\cos\Phi_s$

Line output power = $3.V_r.I.\cos\Phi$

$$\text{Line } \eta = \frac{Line\_output}{Line\_input} = \frac{3.V_r.I.\cos\Phi}{3.V_s.I_s.\cos\Phi_s}$$

Total line losses = Line input - Line output

Or Losses = $3.(V_s.I_s.\cos\Phi_s - V_r.I.\cos\Phi)$

SELECTION OF OVERHEAD LINE CONDUCTORS (ACSR/AAAC)

Following methods have been followed for the above selection:

(a) On the basis of economy, by equating cost of conductor and cost of energy wasted in transmission,

(b) On the basis of rms current and,

(c) On the basis of voltage regulation.

The following initial information are required for selection of OHL conductor

System Voltage	V
Conductor cost constant	P
Annual rate of interest & depreciation	x
Length of overhead line in km	l
Loading capacity in kW	kW
Ambient temperature in ^{0}C	t
System power factor (pf)	cos ø
Span of the overhead line in m	SPN
Load factor	K_l
Electricity tariff in Rs. per kWh	TRF
Permissible voltage regulation	RG

RMS CURRENT

rms current is calculated from the following:

Maximum current $\text{Im} = \dfrac{kW}{\sqrt{3}.V.\cos\Phi}$

Average current $I_{av} = I_m$. load factor $= I_m. K_l$

rms current $= I_{av}$. form factor $= I_{av}.K_f$

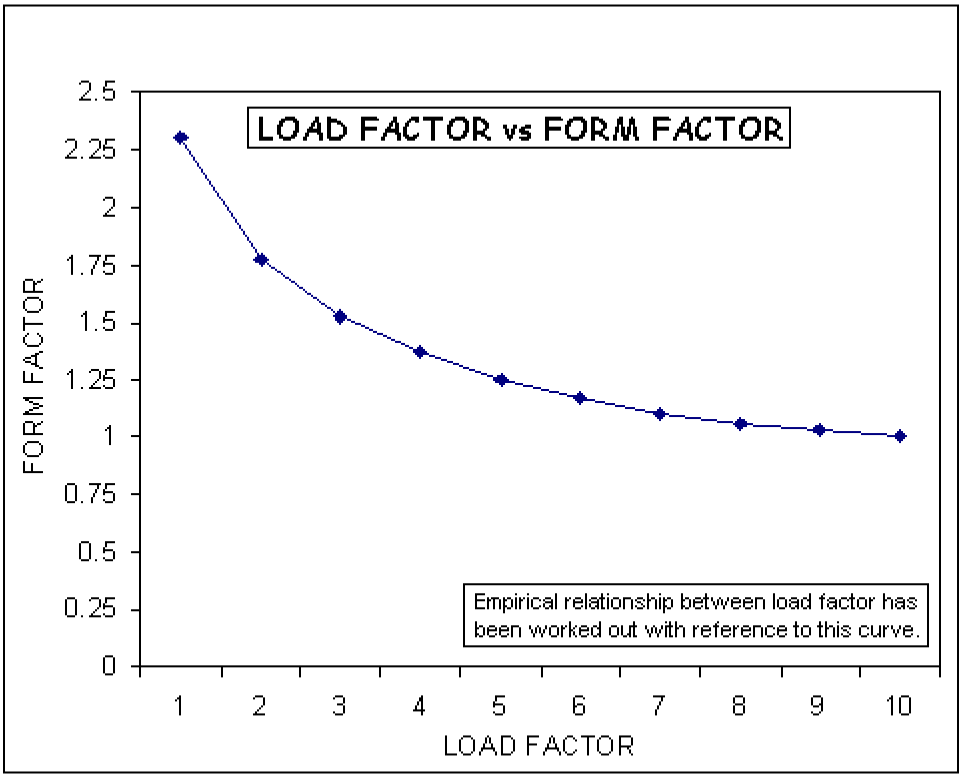
Or $\quad I_{rms} = I_m.K_{l.}K_f$

FORM FACTOR

Form factor is obtained from the following table:

Load factor K_l	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.0
Form factor K_f	2.30	1.93	1.77	1.52	1.37	1.25	1.17	1.10	1.06	1.03	1.0

Form factor at any other value of load factor (say at K_l=0.43) can be obtained as under:



Consider three points x-1, x and x+1 on the load factor line, we observe that LF(x)=0.43 lies between LF(x-1)=0.4 and LF(x+1)=0.5 i.e. a difference of 0.10 (say K_3). The difference from the nearer reference point 0.4 is 0.03 (say K_2). Mathematically it may be written as under:

K_2 = LF(x) - LF(x-1) = 0.43-0.4 = 0.03
K_3 = LF(x+1)- LF(x-1) = 0.5 - .04 = 0.10

Correspondingly, form factor may be calculated in a similar way from the following empirical formula:

$$FF(x) = FF(x-1) - \frac{K_2}{K_3}\left[FF(x-1) - FF(x+1)\right]$$

$$= 1.37 - \frac{3}{10} \times (1.37 - 1.25)$$

$$= 1.334$$

Thus, form factor K_f = 1.334 corresponding to load factor K_l = 0.43.

ESTIMATION OF COST CONSTANT 'P' OF CONDUCTOR

The cost of conductor is directly proportional to its cross sectional area 'a'. According to Kelvin and Kapp cost of overhead line is given by the following empirical relation:

Cost of OHL = P.a + K

Where P is conductor constant dependent on cross sectional area of the conductor.
K is a constant independent of c.s.a. of the conductor.

Estimation of cost of 33 kV OHL with 'DOG' conductor per km as on Sept. 2003:

Sl. no.	DESCRIPTION	QUAN-TITY	AMOUNT in Rs. '000	BASIS OF ESTIMATION
1	Conductor	3.2 km	128	Price list
2	Rail poles, 13m high	13	169	Price list
3	33kV Disc Insulators	39	78	Price list
4	Angles, brackets etc.	13 sets	6.5	Established
5	Earth wire conductor	1 km	25	Price list
6	PCC work at pole sites	13 nos.	6.5	Established
7	Earthing	2 nos.	20	Established
	Sub- total		433	
8	Transportation, erection, bracket and insulator fitting, wire stranding, supervision etc.	25% of sub-total	108.25	As per norms
TOTAL			**541.25**	**Say 542.00**

Estimation of cost of 11 kV OHL with 'DOG' conductor per km as on Sept. 2003:

Sl. no.	DESCRIPTION	QUAN-TITY	AMOUNT in Rs. '000	BASIS OF ESTIMATION
1	Conductor	3.2 km	128	Price list
2	Rail poles, 11m high	13	143	Price list
3	11kV Disc Insulators	39	35.1	Price list
4	Angles, brackets etc.	13 sets	3.9	Established
5	Earth wire conductor	1 km	25	Price list
6	PCC work at pole sites	13 nos.	5.2	Established
7	Earthing	2 nos.	16	Established
	Sub- total		356.2	
8	Transportation, erection, bracket and insulator fitting, wire stranding, supervision etc.	25% of sub-total	89.05	As per norms
TOTAL			**445.25**	**Say 446.00**

Estimation of cost of 6.6 kV OHL with 'DOG' conductor per km as on Sept. 2003:

Sl. no.	DESCRIPTION	QUAN-TITY	AMOUNT in Rs. '000	BASIS OF ESTIMATION
1	Conductor	3.2 km	128	Price list
2	Rail poles, 10m high	13	123.5	Price list
3	6.6kV Disc Insulators	39	35.1	Price list
4	Angles, brackets etc.	13 sets	3.9	Established
5	Earth wire conductor	1 km	25	Price list
6	PCC work at pole sites	13 nos.	5.2	Established
7	Earthing	2 nos.	14	Established
	Sub- total		334.7	
8	Transportation, erection, bracket and insulator fitting, wire stranding, supervision etc.	25% of sub-total	83.68	As per norms
TOTAL			**418.375**	**Say 420.00**

Estimation of cost of 3.3 kV OHL with 'DOG' conductor per km as on Sept. 2003:

Sl. no.	DESCRIPTION	QUAN-TITY	AMOUNT in Rs. '000	BASIS OF ESTIMATION
1	Conductor	3.2 km	128	Price list
2	Rail poles, 9m high	13	110.5	Price list
3	3.3kV Disc Insulators	39	32.5	Price list
4	Angles, brackets etc.	13 sets	3.9	Established
5	Earth wire conductor	1 km	25	Price list
6	PCC work at pole sites	13 nos.	3.9	Established
7	Earthing	2 nos.	12	Established
	Sub- total		315.8	
8	Transportation, erection, bracket and insulator fitting, wire stranding, supervision etc.	25% of sub-total	78.95	As per norms
TOTAL			**394.75**	**Say 395.00**

Estimation of cost of 415 V OHL with 'DOG' conductor per km as Sept. 2003:

Sl. no.	DESCRIPTION	QUAN-TITY	AMOUNT in Rs. '000	BASIS OF ESTIMATION
1	Conductor	3.2 km	128	Price list
2	Rail poles, 8m high	15	46.5	Price list
3	415 V Pin type Insulators	45	4.95	Price list
4	Angles, brackets etc.	15 sets	1.95	Established

5	Earth wire conductor	1 km	25	Price list
6	PCC work at pole sites	15 nos.	3.0	Established
	Sub- total		209.4	
7	Transportation, erection, bracket and insulator fitting, supervision etc.	25% of sub-total	52.35	As per norms
TOTAL			**261.75**	**Say 262.00**

Cost of 550V OHL may be taken equal to that of 415V. Summarised values of the costs of various overhead lines, as on September 2003, are as under:

OHL	33 kV	11 kV	6.6 kV	3.3 kV	415 V
Cost in Rs. '000	542	446	420	395	262

Value of conductor area constant P as taken from the price list of a company issued in the month of *Sept. 2003* is as under:

Sl. No.	**CONDUCTOR**	**Nominal Cu equivalent c.s.a.**	**Cost per km in Rs.**	**Calculated P/3** (d/c)
a	b	c	d	e
1	SQUIRREL	13 sq.mm.	7900	607.7
2	WEASEL	20 sq.mm.	14100	705.0
3	FERRET	25 sq.mm.	16500	660.0
4	RABBIT	30 sq.mm.	19800	660.0
5	MINK	40 sq.mm.	26900	672.5
6	RACOON	48 sq.mm.	28600	595.8
7	DOG	65 sq.mm.	39000	600.0
8	WOLF	95 sq.mm.	69900	735.8
9	PANTHER	133 sq.mm.	93600	703.8
10	GNAT	16 sq.mm.	8000	500.0
11	WEEVIL	19 sq.mm.	11800	621.1
12	LADY BIRD	25 sq.mm.	16100	644.0
13	ANT	30 sq.mm.	19900	663.3
14	FLY	40 sq.mm.	23900	597.5
15	GRASSHOPPER	50 sq.mm.	31600	632.0
16	WASP	65 sq.mm.	39800	612.3
17	CATERPILLAR	110 sq.mm.	70200	638.2
18	CHAFER	130 sq.mm.	80500	619.2
19	ZEBRA	250 sq.mm	153400	613.6
20	SCORPION	325 sq.mm.	201100	618.8
T O T A L				12700.5
Average value of P/3 for the 20 items above				**635.0**
Established avg. value of **P** (including +5% cushion)				**2000**

Cost of OHL = (Cost of conductor etc. proportional to area)
+ (cost independent of cross sectional area).

or $M = P.a + K$

Considering the total cost of OHLs of different voltages K can be obtained for different voltages as under:

$$K_{33} = M_{33} - P.a = 542{,}000 - 2000 \times 65 \text{ (DOG)} = 412000$$

Similarly;

$$K_{11} = M_{11} - P.a = 446{,}000 - 2000 \times 65 \text{ (DOG)} = 316000$$
$$K_{6.6} = M_{6.6} - P.a = 420{,}000 - 2000 \times 65 \text{ (DOG)} = 290000$$
$$K_{3.3} = M_{3.3} - P.a = 395{,}000 - 2000 \times 65 \text{ (DOG)} = 256000$$
$$K_{0.415} = M_{0.415} - P.a = 262{,}000 - 2000 \times 65 \text{ (DOG)} = 132000$$

ENERGY LOSS DURING TRANSMISSION

Losses $= 3 \times I^2{}_{rms} \times r \times l \times 8760 \times 10^{-3}$ in kWh

Where I_{rms} is r.m.s. current in Amps.
r is resistance per km. in ohms
l is length of OHL in km.

$$= 3 \times \left(I_m.K_l.K_f\right)^2 \times \rho \frac{l}{a} \times 8760 \times 10^{-3} \text{ kWh}$$

Where ρ = Specific resistance of cond. material
$= 17.86\ \Omega.mm^2/km$ (for copper)

If TRF be the cost of unit electricity in Rupees then the cost of wasted energy M_l comes to:

$$M_l = 3 \times \left(I_m.K_l.K_f\right)^2 \times \frac{17.86 \times l}{a} \times 8.76 \times TRF \text{ in Rupees.}$$

Now, equating the cost of energy lost per annum to the depreciation of conductor cost, we get the most economical size of conductor cross section as stated below:

Let x = Annual rate of interest and depreciation.

Then, Depreciation $= 1 \times \left(P.a + K\right) \times x$

Depreciation on the part of csa only is = P.a.x.l

Cost of losses $= 3 \times \left(I_m.K_l.K_f\right)^2 \times 17.86 \times \frac{l}{a} \times 8.76 \times TRF$

Or $\quad 3 \times \left(I_m.K_l.K_f\right)^2 \times 17.86 \times \frac{l}{a} \times 8.76 \times TRF = P.a.x$

Or $\quad a^2 = 3 \times 17.86 \times 8.76 \times \left(I_m.K_l.K_f\right)^2 \times \frac{TRF}{P.x}$

Or $\quad a = 21.66473632 \times \left(I_m.K_l.K_f\right) \times \sqrt{\frac{TRF}{P.x}}$ in mm^2

VOLTAGE REGULATION

As per Indian Electricity Rules, voltage regulation in case of low voltage should be within $\pm 6\,\%$ and for high voltage upto 33 kV, it should be between -6% and +9%. In our case, we have considered all voltages below 3.3 kV as low voltages while all voltages equal to 3.3 kV and above have been considered as high voltage.

Voltage Regulation is given by:

$$RG = \frac{Sending\_end\_Voltage - \mathrm{Re}ceiving\_end\_Voltage}{Sending\_end\_Voltage} \times 100$$

Absolute values of voltages should be considered for this purpose.

Voltage regulation $\quad RG = \frac{|V_s| - |V_r|}{|V_s|} \times 100$

V_s is calculated by considering the resistance and reactance of the line when receiving end voltage, power and power factor are given.

CALCULATIONS FOR MW-km OF OVERHEAD LINES (ACSR/ AAAC)

Given conditions are:

Power factor	$\cos\Phi$
Span of the line	SPN
Permissible regulation	RG
System voltage	kV

Span of the lines may be taken as under:

For wooden poles	:	30m - 50m
For RCC/ Rail poles poles	:	50m - 100m
For Steel towers	:	100m - 300m

WEIGHT OF CONDUCTOR ***(Also refer p-36 for mare details)***

Weight of conductor etc. (W) may be expressed in the following term:

$$W = \sqrt{W_1^{\,2} + W_2^{\,2}} \quad \text{kg/m}$$

Where W_1 = Wt. Due to air thrust = Pressure x Area

$$= 33.7 \times \frac{radius \times 2}{1000} \times 1 \quad \text{kg/m.}$$

Where radius is in mm

$$\text{and, } W_2 = \frac{S\tan dard\_wt.\_of\_cond.\_in\_kg/km}{1000}$$

$$= \frac{W'}{1000} \text{ kg/m}$$

SAG OF OH LINE

Sag of the line D is given by:

$$D = \frac{W.L^2}{8 \times T_0} \text{ m}$$

Where W = Weight of conductor etc. in kg/m.
L = Span of the OH Line in m
T_0 = Tension at the bottom of sag of OHL

$$= \frac{(Tensile\_strength\_of\_conductor)}{2}$$

SPACING BETWEEN CONDUCTORS

Spacing between conductors SP is given by the following empirical formula:

$$SP = \left(\sqrt{D} + \frac{V}{150}\right) \text{ m} \qquad \text{(For Aluminium)}$$

Where D = Sag of OHL in m,
V is voltage in kV.

Equivalent spacing is given by d = 1.26 × SP (For Horiz. conductors)

RESISTANCE OF CONDUCTOR

Resistance of the conductor is given by:

$$r = \rho \times \frac{l}{a} = \frac{17.86 \times l}{a} \text{ in ohms } [\rho = 17.86\Omega.mm^2/km \quad \text{for copper}$$

$$= \frac{17.86}{a}\Omega/km$$

Resistance at a temperature t^0 C is given by:

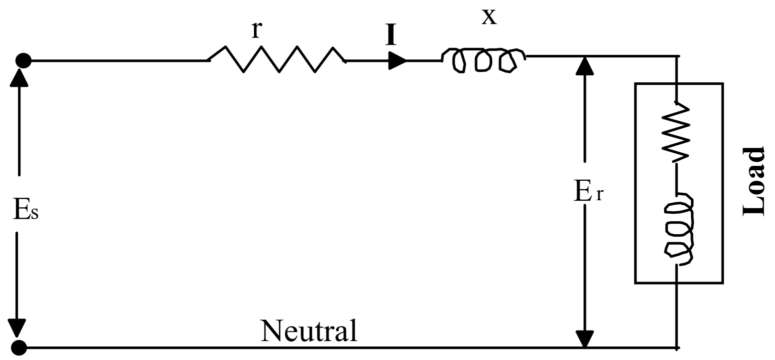
$$r_t = r.\left(\frac{241.5 + t}{241.5 + 20}\right) \qquad \text{Where r is resistance at } 20^0\text{C}$$

Now, MW-km is given by:

$$\text{MW-km} = \frac{\left[V^2 \cos\Phi.\text{Re}\,g(\%)\right]}{100.(r.\cos\Phi + x_l.\sin\Phi)} \quad \text{per phase}$$

Where V is phase voltage in kV.

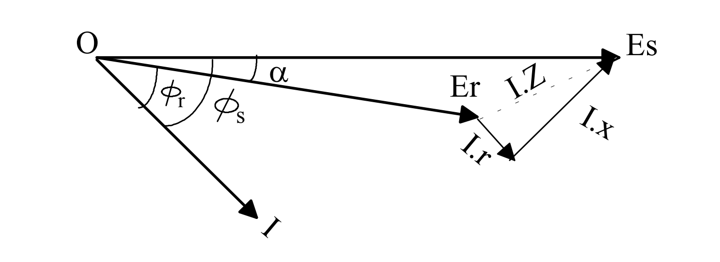
MAXIMUM ACTIVE AND REACTIVE POWER THROUGH AN OVERHEAD LINE



Given conditions are:

r = Resistance / phase/ km
x = Inductive reactance /phase/ km
E_s = Sending end voltage per phase
E_r = Receiving end voltage per phase
I = Load current
Φ_r = Receiving end power factor i.e. Load p.f.

Vector representation of various components is as under:



$$\hat{I} = I.(\cos\Phi_r - j.\sin\Phi_r)$$
$$\hat{E}_r = E_r + j.0$$
$$\hat{Z} = r + j.x$$

$$\begin{aligned}\hat{E}_s &= \hat{E}_r + \hat{I}.\hat{Z} \\ &= \hat{E}_r + I.(\cos\Phi_r - j.\sin\Phi_r)(r + j.x) \\ &= E_r + j.0 + I.r.\cos\Phi_r + I.x.\sin\Phi_r + j.(I.x.\cos\Phi_r - I.r.\sin\Phi_r) \\ &= E_r + I.(r.\cos\Phi_r + x.\sin\Phi_r) + j.I.(x.\cos\Phi_r - r.\sin\Phi_r)\end{aligned}$$

Or $E_s = \sqrt{[E_r + I.(r.\cos\Phi_r + x.\sin\Phi_r)]^2 + [I.(x.\cos\Phi_r - r.\sin\Phi_r)]^2}$

Or $E_s{}^2 = E_r{}^2 + (I.r.\cos\Phi_r + I.x.\sin\Phi_r)^2 + 2.E_r(I.r.\cos\Phi_r + I.x.\sin\Phi_r)$
$+ (I.x.\cos\Phi_r - I.r.\sin\Phi_r)^2$

$$\begin{aligned}&= E_r{}^2 + I^2r^2\cos^2\Phi_r + I^2x^2\sin^2\Phi_r + 2I^2rx\cos\Phi_r.\sin\Phi_r \\ &\quad + 2E_rIr\cos\Phi_r + 2E_rIx\sin\Phi_r + I^2x^2\cos^2\Phi_r \\ &\quad + I^2r^2\sin^2\Phi_r - 2.I^2rx\cos\Phi_r.\sin\Phi_r\end{aligned}$$

$$\begin{aligned}&= E_r{}^2 + I^2r^2(\cos^2\Phi_r + \sin^2\Phi_r) + I^2x^2(\sin^2\Phi_r + \cos^2\Phi_r) \\ &\quad + 2E_rIr\cos\Phi_r + 2E_rIx\sin\Phi_r\end{aligned}$$

$$\begin{aligned}&= E_r{}^2 + 2E_rIr\cos\Phi_r + 2E_rIx\sin\Phi_r + I^2(r^2 + x^2) \\ &= E_r{}^2 + 2.P.r + 2.Q.x + I^2Z^2\end{aligned}$$

Where $P = E_r I \cos\Phi_r$ -> Active power

$Q = E_r.I.\sin\Phi_r$ -> Reactive power

$Z = \sqrt{r^2 + x^2}$ -> Impedance

Therefore, $$E_s^{\,2} = E_r^{\,2} + 2.P.r + 2.Q.x + \frac{P^2 + Q^2}{E_r^{\,2}}\left(r^2 + x^2\right) \qquad \text{(i)}$$

Considering P and Q as variables. Maximum value of P can be found by differentiating the above equation with respect to Q and equating $\frac{dP}{dQ}$ to zero.

Differentiating w.r.t. Q:

$$0 = 0 + 2r\frac{dP}{dQ} + 2x + \frac{r^2 + x^2}{E_r^{\,2}}\left(2P\frac{dP}{dQ} + 2Q\right)$$

When $\frac{dP}{dQ} = 0$ then,

$$0 = 0 + 0 + 2x + \frac{r^2 + x^2}{E_r^{\,2}}\left(0 + 2Q\right)$$

Or $$2x + 2Q\frac{r^2 + x^2}{E_r^{\,2}} = 0$$

Or $$Q = \frac{-x.E_r^{\,2}}{r^2 + x^2}$$

Or $$Q = \frac{E_r^{\,2}.x}{Z^2}$$

Putting this value of Q in equation (i) above, the maximum active power P_{max} can be found as under:

$$E_s^{\,2} - E_r^{\,2} - 2.P.r - 2.x\left(-\frac{E_r^{\,2}.x}{Z^2}\right) - \left(P^2 + \frac{E_r^{\,4}.x^2}{Z^4}\right)\left(\frac{r^2 + x^2}{E_r^{\,2}}\right) = 0$$

Or $$E_s^{\,2} - E_r^{\,2} - 2.P.r + \frac{2E_r^{\,2}.x^2}{Z^2} - \frac{P^2.Z^2}{E_r^{\,2}} - \frac{E_r^{\,4}.x^2}{Z^4}.\frac{Z^2}{E_r^{\,2}} = 0$$

Or $$E_s^{\,2} - E_r^{\,2} - 2.P.r - \frac{P^2.Z^2}{E_r^{\,2}} + \frac{E_r^{\,2}.x^2}{Z^2} = 0$$

Or $$\frac{P^2 Z^2}{E_r^{\,2}} + 2\,\mathrm{Pr} - E_s^{\,2} + E_r^{\,2}\left(1 - \frac{x^2}{Z^2}\right) = 0$$

Or $$\frac{P^2 Z^2}{E_r^{\,2}} + 2\,\mathrm{Pr} - E_s^{\,2} + \frac{E_r^{\,2}.r^2}{Z^2} = 0$$

This is a quadratic equation in P. Solving this, we get:

$$P = \frac{-2r \pm \sqrt{4r^2 - 4\frac{Z^2}{E_r^{\ 2}}\left(-E_s^{\ 2} + \frac{E_r^{\ 2}.r^2}{Z^2}\right)}}{\frac{2.Z^2}{E_r^{\ 2}}}$$

Neglecting the negative value of P, we get P_{max} = P as under:

$$P_{max} = \frac{E_r^{\ 2}}{Z^2}\left(Z.\frac{E_s}{E_r} - r\right) \qquad \text{Watts/ phase}$$

Assuming r = Z in the above equation, maximum power P_{max} can be expressed as under:

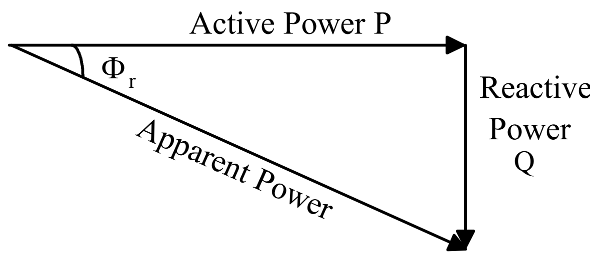
$$P_{max} = \frac{E_r^{\ 2}}{Z^2}.Z\left(\frac{E_s - E_r}{E_r}\right) \qquad \text{Watts/ phase}$$

$$P_{max} = \frac{E_r^{\ 2}}{Z^2} \times \mathrm{Re}\,gulation \qquad \text{Watts/ phase}$$

And,

$$Q_{max} = -\frac{E_r^{\ 2}.x}{Z^2} \qquad \text{VAr/ phase}$$

Power factor angle is also given by:



$$\cos\Phi_r = \frac{Active\_Power}{Apparent\_Power} = \frac{P}{\sqrt{P^2 + Q^2}}$$

$$= \frac{V_r.I.\cos\Phi_r}{V_r.I} \qquad \text{Where } V_r = \text{Receiving voltage}$$

Therefore,

$$\cos\Phi_r = \frac{P}{\sqrt{P^2 + Q^2}}$$

CABLE SELECTION

Cable selection can be done on the following grounds:

1. Considering the rms load current through the cable.
2. Considering the voltage regulation
3. Considering the fault current i.e. the symmetrical breaking capacity.

1. SELECTION BASED ON RMS CURRENT

The effective current for calculating the cable size is taken as under:

Maximum load current through the cable is

Where P = load in kW
V = L-L voltage in kV
Φ = Load power factor

Average current I_{av} is given by:

$$I_{av} = \frac{I_m}{L.F.}$$ Where L.F. = Load Factor (Daily/ Monthly/ Annual)

Form factor (FF) is calculated from the given load factor with the help of following Table:

LF	0.1	0.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
FF	2.3	1.93	1.77	1.52	1.37	1.25	1.17	1.1	1.06	1.03	1

RMS current is then calculated as under:

$$I_{rms} = I_m.LF.FF$$

2. SELECTION BASED ON VOLTAGE REGULATION

The voltage regulation limits, as per the Indian Electricity Rules 1956, are as under:

For low voltages upto 250V	$\pm$ 6%
For medium voltages upto 650V	$\pm$ 6%
For high voltages upto 33kV between	- 6% & + 9%
For extra high voltages >33kV between	- 10% & +12.5%

Frequency variation limits for the supply system is $\pm$ 3%.

EFFECT OF TEMPERATURE

RESISTANCE

The dc resistance of a conductor varies with temperature. The following empirical formulae give the resistance at any other temperature. It may be noted that normally resistances are given in tables at 20^0 C.

(a) $r_t = r_{20}\left(\dfrac{241.5+t}{241.5+20}\right)$ Where t is temp. in ^{0}C

r_{20} is resistance at 20^0C

r_t is temp. at t^0C

(b) $r_t = r_{20}\left[1+\alpha_{20}\left(t-20\right)\right]$

Where $\alpha_{20} = 0.004$ per ^{0}C

= temperature coefficient

INDUCTANCE

Effect of temperature on the inductive reactance is negligible and can be ignored for all practical purposes.

CAPACITANCE

In view of the short length of cables, normally under use, the capacitance has not been considered in its equivalent network.

VOLTAGE REGULATION:

Voltage drop is given by

Drop $= current \times impedance = \hat{I}.\hat{Z}$

Where $\hat{I}$ and $\hat{Z}$ are vectors.

If $\hat{V}_s =$ Sending end voltage then,

$$\hat{V}_r = \hat{V}_s - \hat{I}.\hat{Z}$$

And,

$$\text{Percentage regulation} = \frac{\left|\hat{V}_s\right| - \left|\hat{V}_r\right|}{\left|\hat{V}_s\right|} \times 100$$

3. SELECTION BASED ON FAULT CURRENT

Minimum cross sectional area of the cable is given by:

$$csa_{\min} = \frac{K_t \times I_{sc} \times \sqrt{t}}{K} \qquad \text{sq.mm.}$$

Where I_{sc} is 3 phase short circuit current in kA, t is total break time of C.B. (Opening time + Arcing time) in second, K_t is coefficient corresponding to break time t and K is thermal admissible strength of conductor material (K=116.80 for Cu and K=77.80 for Al).

Break time varies between 0.2 sec and 1.2 sec, K_t is normally taken between 1 and 1.1 for circuit breakers.

Symmetrical short circuit current is calculated by reducing the given network to an equivalent impedance for the worst condition i.e. a 3 phase short circuit.

Fault level at a point in the network is given by:

Fault Level = $\sqrt{3}.V_l.I_{sc}$ MVA When V_l is in kV & I_{sc} is in kA

LOSSES IN CABLES

(i) Conductor $I^2.r$ loss or Copper loss
(ii) Dielectric loss
(iii) Seath loss

CONDUCTOR $I^2.r$ LOSS **(COPPER LOSS)**

As already discussed the resistance of cable conductor at the working temperature is calculated. Let the calculted resistance be r_t. To allow for stranding of conductors 2% is added to r_{tc}. To further allow the multicore structure of cable 2% is further added in the resistance. Finally, the resistance at a temperature t is given by:

$$r_t = 1.02 \times 1.02 \times r_{tc}$$

Losses are calculated with rms current and not with maximum current or average current. RMS current is given by:

$$I_{rms} = I_{\max}.K_f.K_l$$

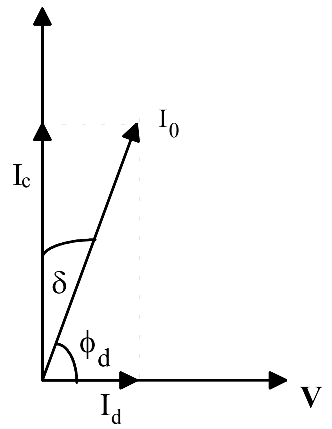
Where K_f and K_l are form factor and load factor respectively.

And maximum load current I_{max} is given by:

$$I_{\max} = \frac{P}{\sqrt{3}.V.\cos\Phi}$$

DIELECTRIC LOSS

The charging current of the cable has two components as shown below:



Given conditions:

I_0= Charging current
I_c= Capacitive current
I_d= Dielectric loss component of charging current
V = Voltage (L-N)
δ = Dielectric loss angle
ϕ_d = Dielectric p.f. angle

To find: Dielectric loss

From the above vector diagram:

$$I_0 = \frac{V}{X_c} = \frac{V}{\frac{1}{\omega.C}} = VC\omega$$

$$I_d = I_0.\cos\Phi_d$$

Dielectric loss = $V.I_d = V.I_0.\cos\phi_d$

Dielectric loss $= V^2 C\omega.\cos\Phi_d$

$= V^2 C\omega.\sin\delta$ When δ is small $\sin\delta \approx \delta$

Therefore, Dielectric Loss $= V^2 C\omega.\delta$ Watts/ phase

And, Total dielectric loss $= 3.V^2 C\omega.\delta$ Watts

The value of δ or the dielectric power factor angle or cable power factor $\cos\Phi_d$ varies with temperature. Typical values may be considered for δ at a suitable temperature.

Power factors of cables at 45^0 C are as under:

Sl.no.	VOLTAGE	Power factor of the cable
1	0.415 kV	0
2	0.55 kV	0
3	3.3 kV	0.007
4	6.6 kV	0.01
5	11 kV	0.012
6	33 kV	0.024

SEATH LOSSES IN CABLES

Sheath loss is given by the following empirical formula by Arnold:

$$\text{Sheath loss} = I^2\left[\frac{78\omega^2}{R_s}\left(\frac{r_m}{d}\right)^2 \times 10^{-9}\right] \text{ Watts per phase}$$

Where I = Current through the conductor,
r_m = Mean sheath radius,
R_s = Sheath resistance in Ω,
d = Distance between conductors,
Note: r_m and d should be in the same units.

However, for all practical purposes, sheath losses are taken equal to 2% of the total losses in the cable.

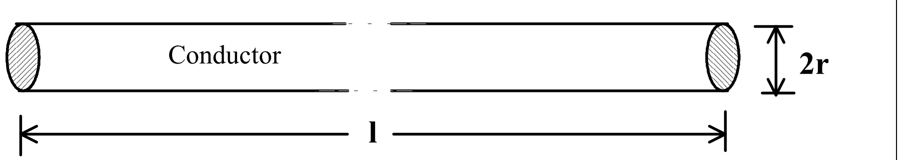
RESISTANCE, INDUCTANCE, CAPACITANCE, SAG AND CONDUCTOR SPACING CALCULATIONS OF OVERHEAD LINES WITH ACSR CONDUCTORS

1. SAG OF OVERHEAD LINES:

While calculating sag of an overhead line, it is assumed that during severe conditions the wind velocity may go upto 40-45 km/hour thereby developing a pressure of about 33.7 kg/m^2.

Effective weight/ tension is due to:

(a) Dead weight of the conductor, w_1
(b) Due to the tension developed during windy days, w_2



Dead weight w_1 can be obtained from tables.

Thrust due to blowing wind can be found as under:

Let r = Radius of the conductor,
l = Length of the conductor,

Thrust = Pressure x Area of exposure per running m

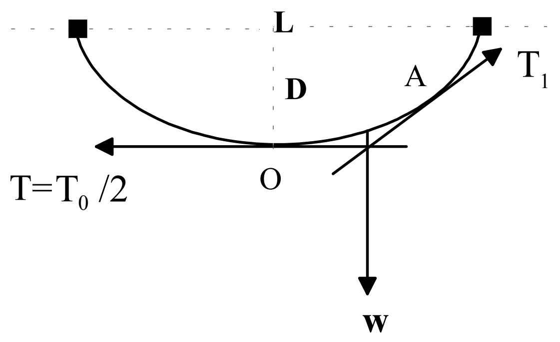
$$w_2 = 33.7 \times \frac{radius \times 2}{1000} \times 1 \quad \text{kg/m.}$$

Where radius r is in mm (converted to m by dividing by 1000)
Therefore,

$$w_2 = \frac{67.4 \times r}{1000} \text{ kg/m} \quad = 0.0674 \times r \quad \text{kg/m}$$

The effective weight of the conductor w is given by:

$$w = \sqrt{w_1^2 + w_2^2}$$



Let span of the overhead line be L m
Let the ultimate tensile strength of the conductor be T_0
Assuming a factor of safety of 2, the permissible tension in the OHL is

$$T = \frac{T_0}{2}$$

Sag of the conductor D in m is given by:

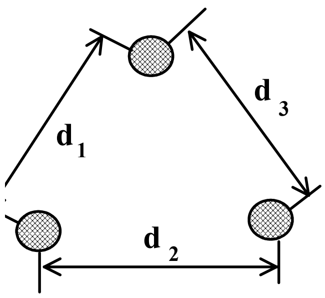
$$D = \frac{w.L^2}{8T} \qquad \text{Where w is in kg/m}$$

Or $$D = \frac{w.L^2 \times 2}{8 \times T_0}$$

Therefore, Sag $$D = \frac{w.L^2}{4.T_0} \qquad \text{in m}$$

2. SPACING BETWEEN CONDUCTORS:

Several empirical formulae have been in practice, however, we will use the following for our purpose. If D be the sag of the OHL in m then:



$$\text{Spacing} = 0.75\sqrt{D} + \frac{V_{kV}}{150} \quad \text{in m for copper}$$

$$\text{Spacing} = \sqrt{D} + \frac{V_{kV}}{150} \quad \text{in m for aluminium}$$

EQUIVALENT SPACING

If the conductors are placed equilaterally/ laterally (Horizontal or Vertical) or in any other shape, the equivalent spacing d is given by:

$$d = \left(\sqrt{d_1.d_2.d_3}\right)^{\frac{1}{3}}$$

= d (For equilaterally placed conductors)
= 1.26 d (For vertical or horizontally placed conductors)

We will now, find the inductance and capacitance by using the above value of equivalent spacing.

3. ***INDUCTANCE OF 3 phase OHL***

Inductance L per phase is given by:

$$L = \left(0.5 + 2.\ln\frac{d}{r}\right) \times 10^{-7} \qquad \text{Henry/ m}$$

Where d = Equivalent spacing in mm
r = Radius of cond. in mm.

Also, Inductive reactance per phase is given by:

$$X_l = 2.\pi.f.L$$

$$= 2\pi \times 50 \times \left(0.5 + 2.\ln\frac{d}{r}\right) \times 10^{-7} \quad \Omega / m$$

Or $$X_l = \pi \times 10^{-2}\left(0.5 + 2.\ln\frac{d}{r}\right) \quad \Omega / km$$

4. ***CAPACITANCE OF 3 phase OHL***

Capacitance of the OHL between one phase and neutral is given by:

$$C = \frac{2\pi\varepsilon}{\ln\frac{d}{r}} \qquad \text{Where } \varepsilon = \frac{1}{36\pi} \times 10^{-9}$$

$$= \frac{2\pi \times \frac{10^{-9}}{36\pi}}{\ln\frac{d}{r}} = \frac{1}{18\times 10^{9}\times \ln\frac{d}{r}} \qquad \text{Farad per m}$$

$$= \frac{1}{18\times 10^{3}\times \ln\frac{d}{r}} \qquad \mu F/m$$

$$C = \frac{1}{18\times \ln\frac{d}{r}} \qquad \mu F/km$$

5. RESISTANCE OF OHL

Resistance per phase of a conductor is given by:

$\rho = \frac{l}{a}$ Where ρ = Sp. resistance of cond. material

a = Cross sectional area of conductor
l = Length of OHL
r = Resistance in Ω

For copper $\rho = 17.86\Omega.mm^2/km$ at 20°C

For Aluminium $\rho = 28.70\Omega.mm^2/km$ at 20°C

For Steel $\rho = 178.0\Omega.mm^2/km$ at 20°C

For our purpose, in ACSR, we will take resistivity of aluminium as 28.7 and 17.86 for its copper equivalent. Moreover, the variation of resistance with temperature is governed by:

$$r_t = r_{20}\left(\frac{241.4+t}{241.5+20}\right) \quad \text{Where } r_{20} \text{ is resistance at 20°C}$$

And also by:

$$r_t = r_{20}\left[1+\alpha_{20}(t-20)\right] \quad \text{Where resistance temp. coefficient}$$

$\alpha_{20} = 0.0038$ for copper
$= 0.0040$ for aluminium

MOST ECONOMICAL POWER FACTOR OF A SYSTEM

Given conditions may be like this:

Active power in kW	PA
Power factor angle of load	ϕ_1
Power factor angle after improvement	ϕ_{21}
Maximum demand rate/kVA	MDR
Cost of pf improvement plant /kVAr	CC
Rate of interest & depreciation	id
Rate of incentive for high pf /month	HPF
Limit above which pf incentive is allowed	HPFL
kW rating of the highest single motor/ load	MkW

It is to explore a condition for most economical pf of the system without loosing the stability of the system.

For this we will define two terms viz.:

(1) Desirable power factor and
(2) Most suitable power factor

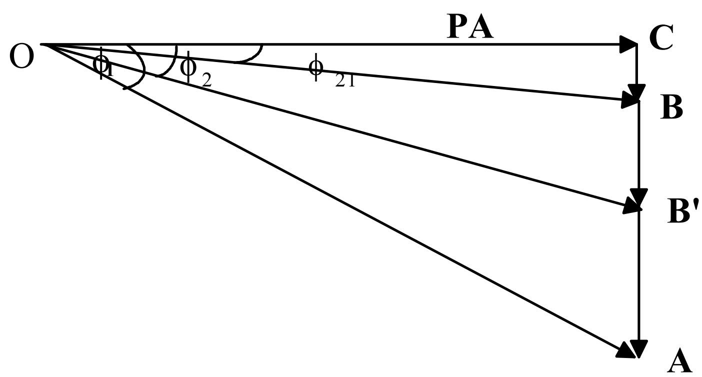
DESIRABLE POWER FACTOR

Desirable power factor is that most economical power factor which does not allow the system to cross the plus unity point, avoiding leading power factor, on switching off the highest motor or electrical load running within the system.

MOST ECONOMICAL POWER FACTOR

Most economical power factor is that power factor which is calculated with due consideration of cost of reactive kVAr versus incentive given on high power factor. This ignores the system stability and other demerits of leading power factor.

Vector diagram for improvement of power factor may be shown like this:



From the above Vector diagram:

Total kVAr = CA = PA. $\tan\Phi_1$

Load kVA = OA = $\dfrac{PA}{\cos\Phi_1}$

kVAr after neutralisation = BC = $PA.\tan\Phi_{21}$

kVA after neutralisation = OB = $\dfrac{PA}{\cos\Phi_{21}}$

Reduction of kVA on power factor improvement is:

OA-OB $= \frac{PA}{\cos\Phi_1} - \frac{PA}{\cos\Phi_{21}}$

Annual saving due to kVA reduction will be equal to

(kVA reduced) x (M.D. rate/kVA/month) x 12

$$= \left(\frac{PA}{\cos\Phi_1} - \frac{PA}{\cos\Phi_{21}}\right) \times MDR \times 12 \qquad \text{(i)}$$

kVAr neutralised = $PA.\tan\Phi_1 - PA.\tan\Phi_{21}$

Cost of neutralised kVAr/ annum is given by:

$$= (kVAr\_neutralized) \times CC \times \frac{id}{100}$$

$$= \frac{CC.id}{100} \times (PA.\tan\Phi_1 - PA.\tan\Phi_{21}) \qquad \text{(ii)}$$

Incentive for high power factor is HPF% /month means that HPF rupees per month is given as incentive for 1% increase in power factor.

Since the limit beyond which incentive is given is HPFL, the annual incentive will be:

Annual incentive = $MD \times (pf - HPFL) \times (Incentive\_rate/month) \times 12$

$$= \frac{PA}{\cos\Phi_{21}} \times (\cos\Phi_{21} - HPFL) \times HPF \times 12$$

$$= \left(PA - \frac{PA.HPFL}{\cos\Phi_{21}}\right) \times HPFL \times 12$$

$$= \left(1 - \frac{HPFL}{\cos\Phi_{21}}\right) \times PA \times HPFL \times 12 \qquad \text{(iii)}$$

Equating the cost involved and saving we get saving S as under:

$$S = \frac{(CC.id.PA)}{100} \times (\tan\Phi_1 - \tan\Phi_{21})$$
$$- \left(\frac{1}{\cos\Phi_1} - \frac{1}{\cos\Phi_{21}}\right) \times PA \times MDR \times 12$$
$$- \left(1 - \frac{HPFL}{\cos\Phi_{21}}\right) \times PA \times HPF \times 12 \qquad \text{(iv)}$$

Now, saving will be maximum when $\frac{dS}{d\Phi_1} = 0$. Equating the above equation no. (iv) w.r.t. Φ_{21} we get:

$$\frac{dS}{d\Phi_2} = \frac{CC.id.PA}{100}\left(0 - \sec^2\Phi_{21}\right)$$

$$-12 \times PA \times MDR \times \left(0 - \sec\Phi_{21}.\tan\Phi_{21}\right)$$

$$-\left(0 - HPFL.\sec\Phi_{21}.\tan\Phi_{21}\right) \times PA \times MDR \times 12$$

Or $$\frac{dS}{d\Phi_2} = \frac{CC.id.PA.\sec^2\Phi_{21}}{100} + 12 \times PA.MDR.\sec\Phi_{21}.\tan\Phi_{21}$$

$$+12 \times PA \times HPF \times HPFL \times \sec\Phi_{21}.\tan\Phi_{21} = 0$$

Or $$-\frac{CC.id.\sec\ \Phi_{21}}{100} + MDR \times 12 \times \tan\Phi_{21}$$

$$+ HPF \times 12 \times HPFL \times \tan\Phi_{21} = 0$$

Or $$\frac{CC.id}{100} - \frac{MDR \times 12 \times \sin\Phi_{21}}{\cos\Phi_{21}} - \frac{12.HPF.HPFL.\sin\Phi_{21}}{\cos\Phi_{21}} = 0$$

Or $$\frac{CC.id}{100} - 12 \times MDR \times \sin\Phi_{21} - 12 \times HPF \times HPFL \times \sin\Phi_{21} = 0$$

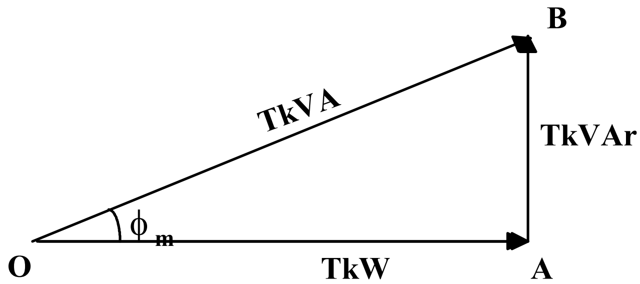
Or $$12 \times \sin\Phi_{21}\left(MDR + HPF + HPFL\right) = \frac{CC.id}{100}$$

Or $$\sin\Phi_{21} = \frac{CC.id}{1200\left(MDR + HPF + HPFL\right)}$$

From here, we can find the ***MOST ECONOMICAL POWER FACTOR*** $\cos\Phi_{21}$ as under:

$$\cos\Phi_{21} = \sqrt{1 - \sin^2\Phi_{21}}$$

NOTE: It may be noted that supply companies normally allow power factor incentive only above 0.95 (lagging).



To find the ***desirable power factor***, the following steps may be added to the most economical power factor:

Let the Highest motor kW be TkW and its power factor be pfm

TkVAr = kVAr released by the highest motor

$$= TkW \times \tan\Phi_m$$

$$= TkW \times \frac{\sin \Phi_m}{\cos \Phi_m}$$

$$= TkW \times \left(\frac{\sqrt{1 - \cos^2 \Phi_m}}{\cos \Phi_m} \right)$$

Or $$TkVAr = TkW \times \left(\frac{\sqrt{1 - pfm^2}}{pfm} \right)$$

Total kVAr = kVAr at most economical power factor
+ kVAr released by highest motor.

Or $B'C = BC + BB'$ (Refer drawing at p-30)

$$= PA.\tan \Phi_{21} + TkW \left(\frac{\sqrt{1 - pfm^2}}{pfm} \right)$$

Or $$\tan \Phi_2 = \frac{B'C}{OC}$$

$$= \frac{PA.\tan \Phi_{21} + TkW \left(\frac{\sqrt{1 - pfm^2}}{pfm} \right)}{PA}$$

Hence, the most suitable or the ***DESIRABLE POWER FACTOR*** of the system $\cos \Phi_2$ is given by:

$$\cos \Phi_2 = \frac{1}{\sqrt{1 - \tan^2 \Phi_2}}$$

CORONA LOSS

Corona is a phenomenon which occurs at high voltages in overhead lines when the potential gradient reaches a critical value of about 30 kV/cm(Peak) equivalent to 21.1 kV(rms). At this voltage the air in between ionises. Corona is associated with a power loss. The voltage at which this phenomenon starts with a hissing sound is known as Disruptive Critical Voltage while the voltage at which this becomes just visible is known as Visual Critical Voltage. The corona is also affected by the smoothness of the conductor, atmospheric pressure, frequency, radius of conductor, spacing between conductors and temperature.

The following empirical formulae have been used for estimating various voltages and loss.

Disruptive Critical Voltage $\quad Vd = 21.1 \times r \times \ln\left(\frac{d}{r}\right)$

Where r and d are in cm. and V_d in kV

For a three phase system, $\quad Vd = \sqrt{3} \times 21.1 \times r \times \ln\left(\frac{d}{r}\right)$

Considering the effects of conductor smoothness, atmospheric pressure and temperature the equation finally comes as:

$$Vd = 21.1 \times r \times m_0 \times \delta \times \ln\left(\frac{d}{r}\right) \qquad \text{kV(rms)/phase}$$

Where air density factor $\delta = \frac{3.93B}{273+t}$

B = Atmospheric pr. in cm of Hg.
t = Temperature in °C
m_0 = Irregularity factor
= > 0.80 to 0.87 for ACSR conductors

Assuming m_0=0.84 and $\delta = 0.9762$ i.e. $m_0.\delta = 0.82$ we get,

$$Vd = 21.1 \times 0.82 \times r \times \ln\left(\frac{d}{r}\right) \qquad \text{kV(rms)/phase}$$

$$= 17.302 \times r \times \ln\left(\frac{d}{r}\right) \quad \text{kV(rms)/phase}$$

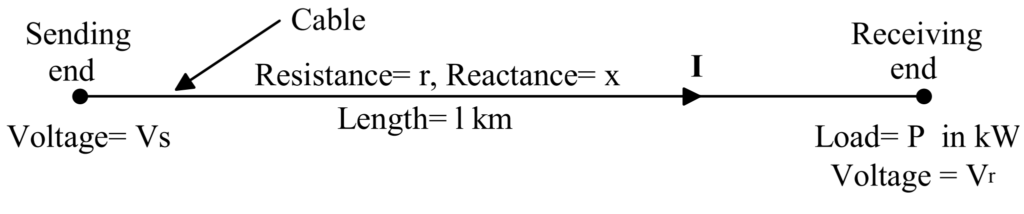
Power loss due to CORONA is given by the following empirical formula:

$$P = \left\{\frac{242.4}{\delta}(f+25)(E_{ph} - V_d)^2 \times \sqrt{\frac{r}{d}}\right\} \times 10^{-5} \quad \text{kW/km of conductor}$$

If l_n be the length of OHL in km, frequency f=50Hz and air density coefficient δ be taken as unity then for a three phase line the losses may be taken as:

$$P = 3 \times 242.4 \times 75 \times (E_{ph} = V_d)^2 \times \sqrt{\frac{r}{d}} \times l_n \times 10^{-5} \qquad \text{kW}$$

VOLTAGE REGULATION AND DROP IN CABLES



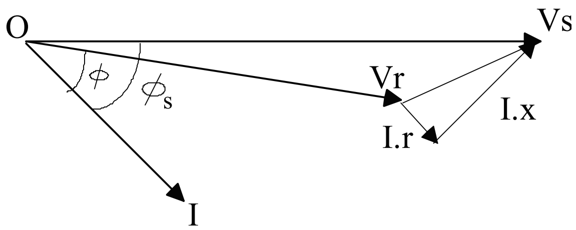
Given conditions are:

Receiving end voltage	V_r in kV
3 phase load in kW	P
Load power factor	$\cos\phi$
Resistance & Reactance	r, x
Length of cable in km	l
Capacitance of the cable	Neglected.

To find the following:

Sending end voltage	V_s
Voltage drop in the cable	I.Z
Voltage regulation	Reg
Sending end power factor	$\cos\phi_s$

The vector diagram of the system is as shown hereunder:



$\hat{I} = I\cos\phi - jI\sin\phi$ $\qquad$ $I = \dfrac{P}{\sqrt{3}V_r\cos\phi}$

r' = Resistance/ phase/ km $\qquad$ x'= Reactance/ phase/ km

r_1 = Resistance/ phase = r' .l $\qquad$ x = Reactance/ phase = x'.l

Impedance per phase= $\hat{Z} = r_1 + j.x$

Voltage drop = $\hat{I}\ \hat{Z} = (I\cos\phi - jI\sin\phi)(r_1 + jx)$

Resistance at t^0 C is given by: $\qquad$ $r = r_1\left(\dfrac{241.5+t}{241.5+20}\right)$

Replacing r_1 by r, the voltage drop is:

$$\hat{I}\ \hat{Z} = I(r\cos\phi + x\sin\phi) + jI(x\cos\phi - r\sin\phi)\ \text{Volts}$$

Sending end voltage is given by:

$$\hat{V}_s = \hat{V}_r + \hat{I}.\hat{Z} = \left[V_r + \frac{I(r.\cos\Phi + x.\sin\Phi)}{1000}\right] + j.I.\frac{(x.\cos\Phi - r.\sin\Phi)}{1000}$$

Sending end power factor $\qquad$ $\cos\Phi_s = \dfrac{V_r\cos\Phi + (Ir/1000)}{V_s}$

Regulation $= \dfrac{V_s - V_r}{V_s} \times 100$

SAG AND TENSION IN OVERHEAD TRANSMISSION LINES

The tension equation of an overhead line is given by:

$$T_2^{\,2}(T_2-\left[\left\{T_1-\frac{l^2W_0^{\,2}q_1^{\,2}\lambda}{24T_1^{\,2}}\right\}-\alpha\left(t_2-t_1\right)\lambda\right]=\frac{l^2W_0^{\,2}q_2^{\,2}\lambda}{24} \qquad \text{(i)}$$

Where T_1 = Tension at temperature t_1 °C
T_2 = Tension at temperature t_2 °C
l = Span of OHL in m
W_0 = Weight of bare conductor in kg/m
q_1 = Loading factor at temperature t_1 °C
q_2 = Loading factor at temperature t_2 °C
α = Coefficient of linear expansion /°C
t_1, t_2 = Initial and final temperatures in °C

Let $\delta = \dfrac{W_0}{A}$ Where A = Conductor CS Area in sq. m.
$T_1 = f_1.A$ Where f_1= Stress at t_1 °C temperature
$T_2 = f_1.A$ Where f_2= Stress at t_2 °C temperature

Substituting these values in equation (i):

$$f_2^{\,2}.A^2(f_2.A-\left[\left\{f_1.A-\frac{l^2A^2.\delta^{\,2}.q_1^{\,2}E.A}{24f_1^{\,2}.A^2}\right\}-\alpha\left(t_2-t_1\right)E.A\right]=\frac{l^2A^2.\delta^{\,2}q_2^{\,2}E.A}{24}$$

or, $$f_2^{\,2}(f_2-\left[\left\{f_1-\frac{l^2.\delta^{\,2}.q_1^{\,2}E}{24f_1^{\,2}}\right\}-\alpha\left(t_2-t_1\right)E\right]=\frac{l^2\delta^{\,2}q_2^{\,2}E}{24}$$

or, $$f_2^2\left(f_2-\left[K-\alpha.t.E\right]\right)=Z \qquad \text{(ii)}$$

Where $$K=\left\{f_1-\frac{l^2.\delta^{\,2}.q_1^{\,2}.E}{24f_1^{\,2}}\right\}$$

$$Z=\frac{l^2\delta^{\,2}q_2^{\,2}E}{24}$$

Finally, the tension equation (i) reduces to (ii). This equation takes into account the effect of temperature, conductor load and wind pressure.

EFFECTIVE WEIGHT OF CONDUCTOR:

Weight of conductor etc. (W) may be expressed in the following term:

$$W = \sqrt{W_0^{\,2} + W_1^{\,2}} \qquad \text{kg/m}$$

Where W_0 = Dead weight of conductor,
W_1 = Weight due to wind.

The dead weight of conductor can be found from tables. IS-398 may be referred if necessary.

The effective wind pressure, if not given, can be obtained from the procedure led down in IS-802(Part-1/Sec-1):1995. The procedure is summarised below:

(a) Select reliability level- For normal towers upto 400kV it is 1.
(b) Select the basic wind velocity V_b as per clause 8.1 & referred map.
(c) Calculate meteorological reference wind speed V_R

$$V_R = \frac{V_b}{K_0} = \frac{V_b}{1.375}$$

(d) Find design wind speed as per clause 8.3, given by:

$$V_d = V_R \times K_1 \times K_2$$

Where K_1 = Risk coefficient
(Value as given in Table-2of IS:802[P1/S1])
K_2 = Terrain roughness coefficient
(Value as given in Table-3of IS:802[P1/S1])

(e) Design wind pressure as per clause 8.4, given by:

$$P_d = 0.6 \times V_d^{\,2}$$

Where P_d = Design wind pressure in N/m^2
V_d = Design wind speed in m/sec

Design wind pressure can be *calculated* or else can be directly *taken* from Table-4 of the referred IS:802(P1/S1) for given Reliability level and Terrain category.

Now, wind load in kg/m can be calculated from the formula given for this purpose in clause 9.2 of the referred IS:802(P1/S1), given by:

$$F_{we} = \frac{P_d \times C_{dc} \times d \times G_c}{9.81} \quad \text{kg/m}$$

Where P_d = Design wind pressure in N/m^2
C_{dc} = Drag coefficient
(1 for conductor and 1.2 for ground-wire)
d = Diameter of conductor in m
G_c = Gust response factor, given in Table 7 of the referred IS:802.

Gust response factor takes into account the turbulence of the wind and the dynamic response of the conductor. The value of Gust factor corresponds to:

(a) Specific Terrain category,
(b) Height above ground and
(c) Ruling span

The average height of conductor/ ground-wire above ground is taken as height of the upper-most conductor upto clamped point, below insulator, less two-third of the sag at minimum temperature and no wind.

Ruling span L of a section having spans of L_1, L_2, L_3, … is given by:

$$L = \sqrt{\frac{L_1^3 + L_2^3 + L_3^3 + ..}{L_1 + L_2 + L_3 + ..}}$$

Sag S may now be calculated from the formula:

$$S = \left(\frac{Actual\_span}{Ruling\_span}\right)^2 \times Sag\_at\_Ruling\_span$$

FACTOR OF SAFETY FOR CONDUCTORS:

1. As per Indian Electricity Rules 1956, the minimum factor of safety for conductors shall be taken as 2 based on their ultimate tensile strength.

2. As per IS:802(P1/S1) the tension limits for Conductors/ ground-wires at everyday temperature and without external load, should not exceed the following limits:

    i. Initial unloaded tension35% of UTS
    ii. Final unloaded tension25% of UTS

    Provided that the *Ultimate Tension* under everyday temperature and 100% design wind pressure, or minimum temperature and 36% design wind pressure does not exceed 70% of the UTS of the conductor/ ground-wire.

3. The IS:802(P1/S1):1995 in its 'Foreword' says like this:

    Some of the major modifications made in this section are as under:
    a) Concept of maximum working load multiplied by the factors of safety as per IE Rules has been replaced by the ultimate load concept.

4. The 3rd of the above three guidelines suggests that there is no need of taking any factor of safety as per IE Rules because it is being taken up in re-assessing the value of conductor load (dead load of conductor and wind load) as calculated on the guidelines given in IS:802(P1/S1):1995. The suggested method of finding re-assessed load in the IS has no-where defined the *'Ultimate Load'*.

    However, if at all, it is taken into consideration, then not only the limit of factor of safety 2 (50% of UTS) changes but also the other limit 35% at 36% wind load should change accordingly.

VOLTAGE DROP & REGULATION IN OVERHEAD LINES

(WHEN SENDING END VOLTAGE IS KNOWN)

GIVEN:

A load of 5000 kW of power factor 0.86 (lagging) is connected at the receiving end of a 6 km long, 3 phase, 11 kV overhead line with ACSR LYNX conductor. The sending end voltage is 11 kV, conductor temperature is 40°C, spacing between horizontally led conductors is 700mm. Annual load factor is 60%.

TO FIND:

Receiving end voltage, sending end of, regulation, voltage drop, maximum losses, rms losses, line efficiency, resistance, reactance, capacitance, surge impedance, load current, disruptive critical voltage, corona loss and annual energy losses.

CALCULATIONS:

From tables, we find:

radius of cond. r_d=9.77mm, resistance/ km = 0.1554, reactance/ km= 0.261
cs area of ACSR LYNX = 183 mm^2 (Aluminium) , 110 mm^2 (Copper equiv.)
Current carrying capacity of conductor =360 A

Capacitance of the line is:

$$C = \frac{l}{18 \times \ln\left(\dfrac{d}{r_d}\right)} = \frac{6}{18 \times \ln\left(\dfrac{700}{9.77}\right)} = 0.078 \mu F / phase$$

Reactance of the line:

x = 0.261 × 6 = 1.566 Ω/phase

Resistance of the line at the given temperature:

$$r = 0.1554 \times \frac{241.5 + 40}{261.5} \times 6 = 0.1673 \times 6 = 1.0037 \ \ \Omega\text{/phase}$$

Given sending end voltage $V_s = \dfrac{11000}{\sqrt{3}} = 6351 \ \text{V}$

Active power $P = \dfrac{5000}{3} = 1666.67 \ \text{kW}$

Reactive Power $Q = P.\tan\Phi = 1666.67 \times 0.5934 = 989 \ \text{kVAr}$ [$\because \cos\Phi = 0.86$

Receiving end voltage is given by:

$$V_r = \sqrt{\frac{AA \pm \sqrt{AA^2 - 4B}}{2}}$$

Where $AA = V_s^{\,2} - 2000(P.r + Q.x)$

$$B = \frac{P^2.Z^2 \times 10^6}{\cos^2 \Phi}$$

Now, $AA = V^2 - 2000 \times (P.r + Q.x)$

$$= 6351^2 - 2000 \times (1666.67 \times 0.1673 \times 6 + 989 \times 0.261 \times 6)$$
$$= 33.89 \times 10^6$$

$$4B = \frac{4P^2.Z^2}{\cos^2\Phi} \times 10^6 = \frac{4 \times 1666.67^2 \times \left[(0.1673 \times 6)^2 + (0.261 \times 6)^2\right]}{0.86^2} \times 10^6$$
$$= 51.98 \times 10^{12}$$

Therefore,

$$Vr = \sqrt{\frac{33.89 \times 10^6 \pm \sqrt{33.89^2 \times 10^{12} - 51.98 \times 10^{12}}}{2}}$$
$$= \sqrt{\frac{33.89 \pm 33.12}{2}} \times 10^3$$
$$= 5788.13 \text{ V } = 5788 \rightarrow (Say)$$

L-L Voltage in kV is: $\frac{5788 \times \sqrt{3}}{1000} = 10.025 \text{ kV}$

Load Current is given by:

$$I = \frac{P}{V_r.\cos\Phi} = \frac{1666.67 \times 10^3}{5788 \times 0.86} = 334.82 \text{ Amps.}$$

Sending end power factor is:

$$\cos\Phi_s = \frac{V_r.\cos\Phi + I.r.l}{V_s}$$ [Refer vector diagram of the text part

$$= \frac{5788 \times 0.86 + 334.82 \times 0.1673 \times 6}{6351} = 0.837$$

Voltage Regulation is given by:

$$\operatorname{Re} g = \frac{|V_s| - |V_r|}{|V_s|} \times 100 = \frac{6351 - 5788}{6351} \times 100 = 8.86\%$$

Voltage drop per phase is given by:

$$I.Z = \sqrt{(V_s.\cos\Phi_s - V_r.\cos\Phi)^2 + (V_s.\sin\Phi_s - V_r.\sin\Phi)^2}$$
$$= \sqrt{(6351 \times 0.837 - 5788 \times 0.86)^2 + (6351 \times 0.547 - 5788 \times 0.51)^2}$$
$$= 622.8$$

L-L Voltage drop is thus: $= 622.8 \times \sqrt{3} = 1078.69$

Also, it can be arrived at by:

Voltage drop per phase is:

$$I.Z = 334.82 \times (0.1673 \times 6 + j\,0.261 \times 6)$$
$$= 622.4 \text{ V}$$

L-L Voltage drop $= 622.4 \times \sqrt{3} = 1078$ V

Line losses in terms of kW is given by:

$$RMS\_Losses = Maximum\_Losses \times (LF \times FF)^2$$

$$RMS\_Losses = 3 \times (Input / phase - Output / phase)(LF \times FF)^2$$

$$= 3 \times (V_s.\cos\Phi_s - V_r.\cos\Phi) \times I \times (LF \times FF)^2$$

$$= 3 \times (6351 \times 0.837 - 5788 \times 0.86) \times 334.82 \times (0.6 \times 1.17)^2 \times 10^{-3}$$

$$= 337.56 \times (0.6 \times 1.17)^2$$

$$= 166.35$$

Annual Energy Loss is given by:

$$Losses = RMS\_Losses \times AnnualHours$$

$$= 166.35 \times 365 \times 24 \ kWh$$

$$= 1457247 \ kWh$$

Overhead line efficiency is given by:

$$\eta_{line} = \frac{Line\_Output}{Line\_Input} \times 100 = \frac{5788 \times 0.86}{6351 \times 0.837} \times 100 = 93.68\%$$

Surge impedance of the line:

$$SI = \sqrt{\frac{L}{C}} = \sqrt{\frac{2\pi fL}{2\pi fC}} = \sqrt{\frac{x}{2\pi fC}}$$

$$= \sqrt{\frac{0.261 \times 6 \times 10^6}{2 \times \pi \times 50 \times 0.078}} = 252.75\Omega$$

Disruptive Critical Voltage is given by:

$$V_d = 21.1 \times m_0 \times \delta \times rd \times \ln\left(\frac{d}{rd}\right)$$

$$= 21.1 \times 0.82 \times 0.977 \times \ln\left(\frac{700}{9.77}\right) \qquad [Since \ m_0 \times \delta = 0.82$$

$$= 72.2 \ kV$$

VOLTAGE DROP & REGULATION IN OVERHEAD LINES

(WHEN RECEIVING END VOLTAGE IS KNOWN)

GIVEN:

A load of 5000 kW of power factor 0.86 (lagging) is connected at the receiving end of a 6 km long, 3 phase, 11 kV overhead line with ACSR LYNX conductor. The receiving end voltage is 11 kV, conductor temperature is 40°C, spacing between horizontally led conductors is 700mm. Annual load factor is 60%.

TO FIND:

Sending end voltage, sending end current, sending end pf, regulation, voltage drop, line efficiency, rms losses, maximum losses, receiving end load current, resistance, reactance, capacitance, Dr. Steinmetz capacitance currents, disruptive critical voltage, corona loss and annual energy losses

CALCULATIONS:

From tables, we find:

radius of cond. r_d=9.77mm, resistance/ km = 0.1554, reactance/ km= 0.261

cs area of ACSR LYNX = 183 mm^2 (Aluminium) , 110 mm^2 (Copper equiv.)

Current carrying capacity of conductor =360 A

Capacitance of the line per km is:

$$C = \frac{l}{18 \times \ln\left(\frac{d}{r_d}\right)} = \frac{6}{18 \times \ln\left(\frac{700}{9.77}\right)} = 0.078 \mu F / phase$$

Reactance of the line:

x = 0.261 × 6 = 1.566 Ω/phase

Resistance of the line at the given temperature:

$$r = 0.1554 \times \frac{241.5 + 40}{261.5} \times 6 = 0.1673 \times 6 = 1.0037 \ \Omega\text{/phase}$$

Given receiving end voltage $Vp = \frac{11000}{\sqrt{3}} = 6351 \text{ V}$

Referring to the text diagram:

Reactance $x_t = \frac{1}{\frac{\varpi C}{6}} = \frac{6}{\varpi C} = \frac{6 \times 10^6}{100 \times \pi \times 0.078} = 244754 \Omega$

Reactance $x_m = \frac{1}{\frac{\varpi 2C}{3}} = \frac{3}{2\varpi C} = \frac{3 \times 10^6}{100 \times 2\pi \times 0.078} = 61188 \Omega$

Current $\hat{I} = \frac{kW}{\sqrt{3}.V.\cos\Phi} = \frac{5000}{\sqrt{3} \times 11 \times 0.86} = 305.15$

Or, $\hat{I} = 305.15 + j0$

Voltage $\hat{V}_r = V_r(\cos\Phi + j\sin\Phi) = 6351 \times (0.86 + j0.51)$

$= 5461.9 + j3239$

Capacitor-1 current is given by:

$$\hat{I}_{c1} = j\frac{\hat{V}_r}{x_t} = j\frac{5461.9 + j3239}{244754} = -0.0132 + j0.0223$$

$= 0.0259\ A \quad (Abs.)$

Line Current-1 is given by:

$$\hat{I}_{s1} = \hat{I} + \hat{I}_{c1} = 305.15 - 0.0132 + j0.0223 = 305.137 + j0.0223$$

Voltage drop in receiving half line is:

$$\hat{I}_{s1}.\hat{Z} = (305.137 + j0.0223) \times \left(\frac{r}{2} + j\frac{x}{2}\right)$$
$$= (305.137 + j0.0223)(0.501856 + j0.783)$$
$$= 153.119 + j238.94$$
$$= 283.76 \rightarrow (Absolute)$$

Mid point voltage is given by:

$$\hat{V}_m = \hat{V}_r + drop\_in\_receiving\_half$$
$$= 5461.9 + j3239 + 153.119 + j238.94$$
$$= 5614.85 + j3479.7$$

Capacitor-2 current is given by:

$$\hat{I}_{c2} = j\frac{\hat{V}_m}{x_m} = j\frac{5614.85 + j3479.7}{61188} = -0.05687 + j0.0918 = 0.108 \rightarrow (Absolute)$$

Line Current-2 is given by:

$$\hat{I}_{s2} = \hat{I}_{s1} + \hat{I}_{c2}$$
$$= 305.137 + j0.0223 + j0.0918 - 0.05687$$
$$= 305.08 + j0.1141$$
$$= 305.08 \qquad (Absolute)$$

Voltage drop in sending half line is:

$$\hat{I}_{s2}.\hat{Z} = (305.08 + j0.114) \times \left(\frac{r}{2} + j\frac{x}{2}\right)$$
$$= (305.08 + j0.114)(0.501856 + j0.783)$$
$$= 153.0192 + j238.94$$
$$= 283.74 \qquad (Absolute)$$

Sending end voltage is given by:

$$\hat{V}_s = \hat{V}_m + drop\_in\_the\_line$$
$$= 5614.85 + j3479.7 + 153 + j238.94$$
$$= 5767.87 + j3718.68$$
$$= 6862.7 \quad (Absolute) \quad (Phase\ voltage)$$
$$= 11.887\ kV \quad (Line\ to\ line\ voltage)$$

Capacitor-3 current is given by:

$$\hat{I}_{c3} = j\frac{\hat{V}_s}{x_t} = j\frac{5767.87 + j3718.68}{244754}$$

Or, $$\hat{I}_{c3} = -0.0151935 + j0.02357 = 0.02804 \rightarrow (Absolute)$$

Sending end current is given by:

$$\hat{I}_s = \hat{I}_{s2} + \hat{I}_{c3} = 305.08 + j0.114 + 0.0236 - 0.01519$$
$$= 305.068 + j0.1376 = 305.07 \quad (Absolute)$$

Vector Angle θ between V_s components is given by:

$$= \tan^{-1}\left(\frac{Vertical\_component\_of\_V_s}{Horizont\_component\_of\_V_s}\right)$$

$$= \tan^{-1}\left(\frac{3718.68}{5767.87}\right) = 0.572657 \rightarrow in\_radians$$

Angle between I_s and I is given by:

$$\alpha = \tan^{-1}\left(\frac{0.1376}{305.068}\right) = 0.000451$$

Therefore, sending end power factor angle is:

$$\Phi_s = 0.572657 - 0.000451 = 0.5722056$$

Or, $$\cos\Phi_s = 0.8407$$

Percentage voltage regulation is given by:

$$\mathrm{Re}\,g = \frac{|\hat{V}_s| - |\hat{V}_r|}{|\hat{V}_s|} \times 100 = \frac{6863 - 6351}{6863} \times 100 = 7.46\%$$

Line losses in kW is given by:

Line losses = Line Input – Line Output

$$= 3 \times (V_s.I_s.\cos\Phi_s - V_r.I.\cos\Phi)$$
$$= 3 \times (6862.7 \times 305.07 \times 0.8407 - 6351 \times 305.15 \times 0.86)$$
$$= 280.3$$

Line losses (rms) in kW is given by:

$$RMS\_Losses = Maximum\_Losses \times (LF \times FF)^2$$
$$RMS\_Losses = 280.3 \times (LF \times FF)^2$$
$$= 280.3 \times (0.6 \times 1.17)^2$$
$$= 138.14 \rightarrow kW$$

Annual Energy Losses is given by:

$$Losses = RMS\_Losses \times AnnualHours$$
$$= 138.14092 \times 365 \times 24\ kWh$$
$$= 1210114\ kWh$$

Overhead line efficiency is given by:

$$\eta_{line} = \frac{Line\_Output}{Line\_Input} \times 100 = \frac{6351 \times 305.15 \times 0.86}{6863 \times 305.07 \times 0.8407} \times 100 = 94.69\%$$

Surge impedance of the line:

$$SI = \sqrt{\frac{L}{C}} = \sqrt{\frac{2\pi fL}{2\pi fC}} = \sqrt{\frac{x}{2\pi fC}}$$

$$= \sqrt{\frac{0.261 \times 6 \times 10^6}{2 \times \pi \times 50 \times 0.078}} = 252.75\Omega$$

Disruptive Critical Voltage is given by:

$$V_d = 21.1 \times m_0 \times \delta \times rd \times \ln\left(\frac{d}{rd}\right)$$

$$= 21.1 \times 0.82 \times 0.977 \times \ln\left(\frac{700}{9.77}\right) \qquad [Since\ m_0 \times \delta = 0.82$$

$$= 72.2\ kV$$

Voltage drop/ phase is given by:

(a) Vector sum of I.Z drops of both halves of the line
(b) Difference Sending end and Receiving end voltages

(a) $V_{IZ} = 153.119 + j238.94 + 153.019 + j238.94$
= 306.138 + j477.88
= 567.53 (Phase Voltage)
= 982.96 (Line Voltage)

(b) $V_{diff} = Sending\_Voltage - \mathrm{Re}ceiving\_Voltage$
= 5678 + j3719 – (5462 + j3239)
= 306 + j480
= 567.52 (Phase Voltage)
= 985.96 (Line Voltage)

(The program has used second method i.e. (b) for calculations).

NOTE: While going through the above calculations, it would have been observed that results obtained have some fractional variation. This is due to the consideration of parameter values upto several number of digits after the decimal. However, the final values are correct upto the shown places of decimal.

VOLTAGE REGULATION & DROP WHEN SENDING END VOLTAGE IS KNOWN

INPUT PARAMETERS:

Sl.No.	Description	INPUT	Remarks
1	Sending end voltage in kV	11	
2	Receiving end Load in kW	5000	
3	Power factor of the load	0.86	
4	Load factor of the system	0.6	
5	Name of overhead line Conductor	LYNX	
6	Length of the overhead line in km	6	
7	Equiv.spacing between conductors in mm	700	
8	OHL Conductor temperature in °C	40	

RESULT GENERATED BY THE PROGRAM:

S.N.	Description	Unit	OUTPUT	Remarks
1	Receiving end load shared by conductor path	kW	5000	
2	Receiving end voltage of the OHL	kV	10.025	
3	Sending end power factor	Factor	0.8367	
4	Percentage voltage regulation	%	8.86	
5	Voltage drop in the overhead line/ phase	Volts	622.78	
6	Annual energy losses in the overhead line	kWh	1457247	
7	Total line losses (Maxm.)	kW	337.56	
8	Total line losses (rms value)	kW	166.35	
9	Resistance/ conductor of the OHL at 40°C	Ohms	1.0037	
10	Inductive React./ conductor of the OHL.	Ohms	1.566	
11	Capacitive React./ conductor of the OHL.	Ohms	-	
12	Capacitance/ conductor of the OHL.	MFD	0.078	
13	Form factor of the system.	Factor	1.17	
14	Line efficiency of the OHL system.	%	93.68	
15	Surge impedance of the OHL.	Ohms	252.747	
16	Current through conductor of the OHL	Amps.	334.8	
17	Disruptive critical voltage/ phase	kV	72.2	
18	Equivalent impedance/ phase of OHL	Ohms	1.8601	
19	Equivalent Cu cs area of conductor	sq.mm.	110	
20	Equivalent Al cs area of conductor	sq.mm.	183	
21	Current carrying capacity of conductor	Amps.	360	

REGULATION & DROP WHEN RECEIVING END VOLTAGE IS KNOWN

INPUT PARAMETERS:

Sl.No.	Description	INPUT	Remarks
1	Receiving end voltage in kV	11	
2	Receiving end Load in kW	5000	
3	Power factor of the load	0.86	
4	Load factor of the system	0.6	
5	Name of overhead line conductor	LYNX	
6	Length of the overhead line in km	6	
7	Equiv.spacing between conductors in mm	700	
8	OHL Conductor temperature in °C	40	

RESULT GENERATED BY THE PROGRAM:

S.N.	Description	Unit	OUTPUT	Remarks
1	Receiving end load shared by conductor path	kW	5000	
2	Sending end voltage of the OHL (L-L)	kV	11.887	
3	Sending end current/ phase of the OHL	Amps.	305.07	
4	Sending end power factor of the OHL	Factor	0.8407	
5	Percentage voltage regulation of the line	%	7.46	
6	Annual energy losses in the overhead line	kWh	1210114	
7	Total line losses (maximum in eq. kW)	kW	280.32	
8	Total line losses (rms value in eq. kW)	kW	138.14	
9	Resistance/ conductor of the OHL at 40°C	Ohms	1.0037	
10	Inductive React./ conductor of the OHL	Ohms	1.566	
11	Line efficiency of the OHL system.	%	94.69	
12	Receiving end current/ phase of the OHL	Amps.	305.15	
13	Form factor of the system.	Factor	1.17	
14	Total Capacitance/ phase of the OHL	MFD	0.078	
15	Receiving end capacitor current	Amps.	0.026	
16	Overhead line mid point capacitor current	Amps.	0.108	
17	Sending end capacitor current	Amps.	0.026	
18	Disruptive critical voltage/ phase	kV	72.2	
19	Equivalent impedance/ phase of OHL	Ohms	1.8601	
20	Equivalent Cu cs area of conductor	sq.mm.	110	
21	Equivalent Al cs area of conductor	sq.mm.	183	
22	Current carrying capacity of conductor	Amps.	360	
23	Capacitive React./ conductor of the OHL	k.Ohms	40.8	
24	Voltage DROP per phase in the OHL	Volts	567.5	

SELECTION OF MOST ECONOMICAL OVERHEAD LINE CONDUCTOR (SAMPLE CALCULATION)

GIVEN:

Limiting size of OHL conductor is LYNX, system voltage is 11kV, inflated value of conductor constant K_0 is 2150, length of OHL is 6km, loading capacity is 5000kW at 0.86 load power factor, conductor temperature is 40°C, annual interest and depreciation is 18%, span of OHL is 90m, annual load factor is 0.6, cost of unit energy is Rs. 2.30 and permissible voltage regulation is 9%.

TO FIND:

Most suitable OHL, receiving end voltage, sending end power factor, voltage regulation, voltage drop, rms line losses, corona loss, annual energy loss, resistance, reactance and capacitance per phase of the line, selected conductor on the basis of load current, most economical conductor and its cross sectional area, sag of OHL, recommended spacing of conductors, standard capacity of OHL in kWkm at 40°C and cost of OHL per km.

From Tables for LYNX conductor:

Resistance of the conductor/ phase at 20°C = 0.1554 Ω / km

Reactance of the conductor/ phase x = 0.261 Ω / km

Resistance at 40°C is given by:

$$r = 0.1554 \times \frac{241.5 + 40}{261.5} = 0.1673 \ \Omega / km$$

Now, $r\cos\Phi + x\sin\Phi = 0.1673 \times 0.86 + 0.261 \times 0.51 = 0.277$

From the initial given values and assuming percentage regulation as 6% at 11kV, number of parallel circuits may be estimated by the following:

$$kWkm = \frac{kV^2 \times pf \times rg \times 100}{r\cos\Phi + x\sin\Phi} = \frac{11^2 \times 0.86 \times 0.06 \times 1000}{0.277} = 22540$$

Number of parallel paths $\dfrac{kW \times km}{kWkm} = \dfrac{5000 \times 6}{22540} = 1.33 \Rightarrow 2$

Power to be transmitted per circuit $= \dfrac{kW}{ckt} = \dfrac{5000}{2} = 2500kW$

From the Form factor curve, FF=1.17 corresponding to LF=0.6

Load current $I_m = \dfrac{kW}{\sqrt{3}V\cos\Phi} \dfrac{5000}{\sqrt{3} \times 11 \times 0.86} = 305.2 Amps$

RMS current $I_{rms} = I_m \times LF \times FF = 305.2 \times 0.6 \times 1.17 = 214.22 Amps$

A. SELECTION ON THE BASIS OF ECONOMICAL CONDITIONS:

Most economical cross sectional area of the OHL conductor is given by (Refer text part of this Software):

$$csa = 21.665 \times \frac{I_{rms}}{ckt}\sqrt{\frac{100 \times TRF}{K_0 \times id \times ckt}} \quad \text{mm}^2$$

Where TRF is cost of unit energy
K_0 is area cost index (refer text)
Id is percentage rate of interest & depreciation

$$csa = 21.665 \times \frac{214}{2}\sqrt{\frac{100 \times 2.3}{2150 \times 18 \times 2}} = 126.37 mm^2$$

From Tables, it may be inferred that TWO circuits of LYNX conductor are not capable to reach the desired capacity. Hence, THREE circuits are taken and find the economical cross sectional area as under:

$$csa = 21.665 \times \frac{214}{3}\sqrt{\frac{100 \times 2.3}{2150 \times 18 \times 3}} = 68.78 mm^2$$

From Tables, we find that THREE circuits of TIGER conductor are sufficient to carry the desired load under the most economical condition.

B. SELECTION ON THE BASIS OF CURRENT CAPACITY:

Taking a de-rating factor corresponding to 33.3% de-rated capacity of the OHL, the current for selection of conductor ids given by:

$$I_s = 1.6 \times \frac{I_m}{ckt} = \frac{1.6 \times 305.2}{2} = 244.16 A$$

From the Tables, it can be inferred that TWO nos. of TIGER conductors are capable to carry the given load.

FINAL SELECTION AND VALUES:

Finally we find in this case, logically, THREE circuits with TIGER conductor suitable to carry the given load under the given conditions.

Now, Phase voltage is given by:

$$kV_p = \frac{1000 \times kV}{\sqrt{3}} = \frac{1000 \times 11}{\sqrt{3}} = 6351 \ V$$

From Tables, we find for ACSR TIGER conductor:

r = 0.2221, x = 0.282,
conductor radius rd = 8.26,
dead weight of conductor/km = 604 kg and
tensile strength = 5758

Load per circuit = $\dfrac{kW}{ckt} = \dfrac{5000}{3} = 1666.67kW$

Resistance at 40°C $\quad r = 0.2221 \times \dfrac{241.5 + 40}{261.5} = 0.2391\Omega$

For a 6.0km long line $\quad$ *r = 6 × 0.2391 = 1.4345 and*
x = 6 × 0.282 = 1.692

Active power per phase $\quad kWP = \dfrac{Load\,/\,circuit}{3} = \dfrac{1666.67}{3} = 555.6 \Rightarrow 556$

Reactive power per phase $kWQ = \dfrac{kWP \times \sin\Phi}{\cos\Phi} = \dfrac{556 \times 0.51}{0.86} \approx 329$

Referring to text:

$$\begin{aligned} AA &= kV_p^{\;2} - 2000 \times (kWP \times rct + kWQ \times x) \\ &= 6351^2 - 2000 \times (556 \times 1.4345 + 329 \times 1.692) \\ &= 37.625 \times 10^6 \end{aligned}$$

And, $\quad B = \dfrac{10^6 \times kWP^2 \times (r^2 + x^2)}{PF^2}$

$$= \frac{10^6 \times 556^2 \times (1.4345^2 + 1.692^2)}{0.86^2}$$

$$= 2.056 \times 10^{12}$$

Hence, $\quad 4B = 8.23 \times 10^{12}$

Now, $\quad E = \sqrt{AA^2 - 4B} = \sqrt{(37.625)^2 - 8.23 \times 10^{12}} = 37.515 \times 10^6$

And $\quad E_{r1} = \dfrac{AA + E}{2} = \dfrac{37.625 + 37.515}{2} \times 10^6 = 37.57 \times 10^6$

Therefore, receiving end voltage E_r is:

$E_r = \sqrt{E_{r1}} = \sqrt{37.57 \times 10^6} = 6129V$ *=> 10.615kV (L-L)*

Sending end power factor is given by:

$$PF_s = \frac{E_r \cos\Phi + \left(\frac{1000 \times kWP}{E_r \cos\Phi}\right) \times r}{kV_p}$$

$$= \frac{6129 \times 0.86 + \left(\frac{1000 \times 556}{6129 \times 0.86}\right) \times 0.4345}{6351}$$

$$= 0.8538$$

Losses (rms) is given by:

$$LL = ckt \times 3\left(\frac{I_{rms}}{ckt}\right)^2 \times \frac{r}{1000} \quad kW$$

$$= 3 \times 3 \times \left(\frac{214}{3}\right)^2 \times \frac{1.4345}{1000} = 65.83\ kW$$

Effective weight of Conductor:

Weight due to air thrust, assuming 33.7 kg/m² as the air pressure:

$$W1 = 33.7 \times \frac{2 \times rd \times l}{1000} \qquad kg/m$$

$$= 33.7 \times \frac{2 \times 8.26 \times 1}{1000}$$

$$= 0.5567 kg/m$$

Dead weight of conductor (from Tables) $W_2 = 0.604\ kg/m$

Effective weight of conductor:

$$W = \sqrt{W_1^2 + W_2^2} = \sqrt{0.557^2 + 0.604^2} = 0.8214 kg/m$$

Taking factor of safety 2 (as per IER-1956), the OHL conductor tension is:

$$T = \frac{Ultimate\_Tensile\_Strength}{2} = \frac{5758}{2} = 2879 kg$$

Maximum Sag of overhead line is given by:

$$Sag = \frac{WL^2}{8 \times T} = \frac{0.821 \times 90^2}{8 \times 2879} m = 288.7 mm$$

Spacing between conductors is given by:

$$SPC = 1.26 \times \left(\sqrt{SG} + \frac{kV}{150} \right) \quad m$$
$$= 1260 \times \left(\sqrt{0.2887} + \frac{11}{150} \right) = 769.4mm$$

Capacitance per is given by:

$$C = \frac{l}{18 \times \ln\left(\frac{SP}{rd}\right)} = \frac{6}{18 \times \ln\left(\frac{769}{8.26}\right)} = 0.0735\mu F$$

Disruptive Critical Voltage is given by:

$$V_c = 17.302 \times rd \times \ln\left(\frac{SP}{rd}\right) \times 100$$
$$= 17.302 \times 8.26 \times \ln\left(\frac{769}{8.26}\right) \times 100$$
$$= 64792.7V$$
$$= 64.8kV$$

Total Energy Loss in the OHL is:

$$LLW = LL \times 8760 = 65.83 \times 8760 = 575444.4\ kWh$$

Line Efficiency is given by:

$$\eta = \frac{kWP}{kWP + \left(\frac{LL}{3 \times ckt}\right)} = \frac{556}{556 + \left(\frac{65.83}{3 \times 3}\right)} \times 100 = 98.7\%$$

Voltage Regulation is given by:

$$\mathrm{Re}\,g = \frac{kV_p - E_r}{kV_p} \times 100 = \frac{6351 - 6129}{6351} \times 100 = 3.4955$$

MWkm capacity of the line is given by:

$$MWkm = \frac{V^2 \cos\Phi \times RG}{r\cos\Phi + x\sin\Phi}$$

Here, $V = 11$, $\cos\Phi = 0.86$, $RG = 0.09$ *for 11kV,*
$r = 0.2391$ *at 40°C,* $x = 0.282$

$$MWkm = \frac{11^2 \times 0.86 \times 0.09}{0.349446} = 26.8007$$

Cost of overhead line per km is given by:

$$\cos t = K_0 \times Cond\_area + K_{11} \times \frac{K_0}{K}$$ *(Please refer text*

Where K_0 = *Value of index as on date*
K_{11} = *Constant of the program (takes by default)*
K = *Base value of area index (takes by default)*

$$\cos t = 2150 \times 80 + 316000 \times \frac{2150}{2030}$$ *for single circuit with TIGER*

$$= 506680$$

Cost of Selected OHL per km is given by:

$$\cos t = K_0 \times Cond\_area \times ckt + K_{11} \times \frac{K_0}{K} \times Int\left(\frac{ckt}{2}\right)$$

$$= 2150 \times 80 \times 3 + 316000 \times \frac{2150}{2030} \times Int\left(\frac{3}{2}\right)$$

$$= 2150 \times 80 \times 3 + 316000 \times \frac{2150}{2030} \times 2$$

$$= 1185360$$

(Rs. Eleven lakhs eightyfive thousand and sixty)

CABLE SELECTION (SAMPLE CALCULATION)

GIVEN:

Limiting size of cable is 240 mm², receiving end voltage is 3.3kV, percentage regulation should be limited to 9%, cable conductor temperature is 40°C, annual load factor is 0.6, conductor material is copper, cable length is 300m, load at the receiving end is 300kW at 0.86 power factor. Symm. Short circuit current is 5kA and breaking time of switchgear is 0.75 sec. Thermal admissibility constant for Cu is 116.8 Amp/mm².

TO FIND:

Most suitable cable, load current, regulation, sending end voltage, voltage drop, maximum and rms losses in the cable, resistance, reactance and capacitance per phase, cable selected on the basis of rms current, cable selected on the basis of regulation, cable selected on the basis of fault current, line efficiency, rms current, sending end power factor, dielectric loss, sheath loss and annual energy loss in the selected cable.

A. CABLE SELECTION BASED ON RMS CURRENT:

Load current $I_m = \dfrac{P}{\sqrt{3}.V.\cos\Phi} = \dfrac{300}{\sqrt{3}\times 3.3\times 0.86} = 61.03A$

Average current $I_{av} = \dfrac{I_m}{FF} = \dfrac{61.03}{1.17} = 52.16A$

RMS Current $I_{rms} = I_m \times LF \times FF = 61.03 \times 0.6 \times 1.17 = 42.84\ A$

Selection current $I_s = 2 \times I_{rms} = 2 \times 42.84 = 85.68\ A$ *=> 1 × 25 mm² Copper*

B. CABLE SELECTION BASED ON VOLTAGE REGULATION:

Regulation has been set not to exceed 9%. Take the case of cable selected by the program and check for its suitability:

For the selected one number of 2.5mm² copper cable:

r/ km = 7.118 x/ km = 0.204

At 40°C the resistance and reactance of 300m long cable will be:

$$r = 7.118\times 0.3\times \frac{241.5+40}{241.5+20} = 2.2987\Omega$$

x = 0.204 0215 0.3 = 0.0612 Ω *and,*

C = 0.18 × 0.3 = 0.054 μF

Voltage drop is given by:

$$\begin{aligned}\hat{I}.\hat{Z} &= I\left[(r\cos\Phi + x\sin\Phi) + j(x\cos\Phi - r\sin\Phi)\right]\\ &= 61.03\times\left[(2.2987\times 0.86 + 0.0612\times 0.51) + j(0.0612\times 0.86 - 2.2987\times 0.51)\right]\\ &= 122.554 - j68.336\\ &= 140.32(Absolute)\end{aligned}$$

Sending end voltage is given by:

$$\begin{aligned}\hat{V}_s &= \hat{V}_r + \hat{I}.\hat{Z}\\ &= (1905.256 + j0) + 122.556 - j68.336\\ &= 122.554 - j68.336\\ &= 2028.95(Absolute)\end{aligned}$$

Regulation is given by:

$$\operatorname{Re} g = \frac{V_s - V_r}{V_s} = \frac{2028.95 - 1905.256}{2028.95} = 6.10\%$$

It will be observed that regulation is more than 9% in case we consider 1.5 mm² copper cable. So the cable selected on the basis of regulation is one no. of 2.5 mm² copper.

C. CABLE SELECTION BASED ON FAULT CURRENT:

Consider the symmetrical 3-phase fault current as the basis of selection. The minimum cross sectional area of the cable is given by:

$$a = \frac{1.08 \times Short\_ckt\_current\_Amps \times \sqrt{Break\_time\_\sec}}{Thermal\_admissibility\_cons\tan t\_K} \; mm^2$$

Where K = 116.80 Amp/mm² for copper conductor
K = 77.80 Amp/mm² for aluminium conductor

$$a = \frac{1.08 \times I_{sc} \times \sqrt{t}}{K} = \frac{1.08 \times 5000 \times \sqrt{0.75}}{116.8} = 40.04 mm^2$$

So, the selected cable on the basis of short circuit fault current is the nearest higher size cable i.e. 50 mm².

Summarizing all the three cases dealt above:

By rms current : *1 × 25 mm² Cu cable*
By Voltage Regulation : *1 × 2.5 mm² Cu cable*
By fault current : *1 × 50 mm² Cu cable*

So, the recommended cable will be the highest one i.e. one no. of 50 mm² Cu cable.

FINAL VALUES:

r/km = 0.378 x/km = 0.08

At 40°C the values for the recommended cable will be:

$$r = 0.378 \times 0.3 \times \frac{281.5}{261.5} = 0.1221\Omega$$

$x = 0.08 \times 0.3 = 0.024\ \Omega$

$C = 0.46 \times 0.3 = 0.138\ \mu F$

Voltage drop is given by:

$$\hat{I}.\hat{Z} = 61.03 \times \left[(0.1221 \times 0.86 + 0.024 \times 0.51) + j(0.024 \times 0.86 - 0.1221 \times 0.51)\right]$$
$$= 7.1555 - j2.541$$
$$= 7.5933(Absolute)$$

Sending end voltage is given by:

$$\hat{V}_s = (1905.256 + j0) + 71555 - j2.541$$

$= 1912.41 - j2.541$
$= 1912.41(Absolute)$
$\Rightarrow 3312.4V \rightarrow (L-L)$

Regulation is now given by:

$$\mathrm{Re}\,g = \frac{V_s - V_r}{V_s} \times 100 = \frac{1912.41 - 1905.256}{1912.41} \times 100 = 0.3741\%$$

Now, $\cos\Phi = 0.86 \rightarrow\rightarrow \Phi = 30.6834$

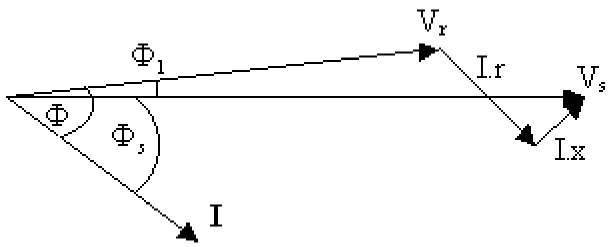
$$\tan\Phi_1 = \frac{-2.541}{1912.41} = -0.00133$$

$$\Phi_1 = Arc\tan(-0.00133) \times \frac{180}{\pi}$$
$$= -\ 0.076$$

Sending end power factor angle:

$\Phi_s = \Phi + \Phi_1 = 30.6834 - 0.076 = 30.6074$

Or $\cos\Phi_s = 0.8606$



LOSS COMPONENTS AND LOSSES IN THE SELECTED CABLE:

Losses (rms) $= 3 \times I_{rms}^{\ 2} \times r = 3 \times 42.84^2 \times 0.1221 = 672.26Watts$

Losses (Max) $= 3 \times I_m^{\ 2} \times r = 3 \times 61.03^2 \times 0.1221 = 1364.3Watts$

Dielectric Losses $= 3V^2 C\omega\delta = 3 \times 1.9053^2 \times 0.138 \times 2 \times \pi \times 50 \times 0.007$
= 3.3 Watts

Sheath Loss is given by:

$$L_{sheath} = 2\%\_of\_(rms + dielectric\_Losses)$$
$$= 0.02 \times (672.26 + 3.3)$$
$$= 13.51Watts$$

Total RMS Losses is therefore:

$$L_{rms} = 672.26 + 3.3 + 13.51 = 689.07 Watts$$

And Total Losses (Maximum) is:

$$L\max = 1364.3 + 3.3 + 13.51 = 1381.11 Watts$$

Line efficiency $\eta = \frac{Output}{Output + Losses} \times 100 = \frac{300}{300 + 1.381} \times 100 = 99.54\%$

Annual Energy Loss in kWh units is given by:

$$\begin{aligned} Losses &= Total\_RMS\_Losses \times 8760 \\ &= 0.689 \times 8760 \\ &= 6035.64 \\ &= 6036\ kWh \end{aligned}$$

So, the annual energy loss in the selected cable will be 6036 kWh only.

GENERATED RESULTS OF CABLE SELECTION

INPUT DATA:
Limiting standard Cable size in m² = 240
Receiving end voltage in kV(L-L) = 3.3
Permissible % voltage regulation (upto 60) = 9
Load at the receiving end in kW = 300
Power factor of the load = 0.86
Load factor of the cable = 0.6
Length of the cable in m = 300
Mention the type of cable (Al/Cu) = cu
Maximum Cable conductor temp. in °C = 40
Symmetrical short circuit current in kA = 5
Break time of ckt. breaker in sec (0.2 - 1.2) = 0.75

OUTPUT RESULTS:
Cable Selected on the basis of Fault Current = 1 Cable(s) of 50 sq.mm.
Cable Selected on the basis of RMS Current = 1 Cable(s) of 25 sq.mm.
Cable Selected on the basis of Volt. Reguln. = 1 Cable(s) of 2.5 sq.mm.
Recommended Cable = 1 Cable(s) of 50 sq.mm.

CALCULATED PARAMETERS OF THE RECOMMENDED CABLE
Required number of the cable lengths in parallel = 1
Cross Sectional Area of the selected cable sq.mm. = 50.0
Percentage voltage regulation (%) = 0.374
Voltage drop in the cable/phase in Volts = 7.6
Annual energy loss in the selected cable in kWh = 6036
Percentage line efficiency of the cable (%) = 99.5
Resistance of the cable/phase/conductor in ohms = 0.1221
Ind. reactance of the cable/phase/conductor in ohms = 0.0240
Capacitance of each cable/phase in MFD = 0.1380
Total losses in the cable (Average)- kW component = 0.689
Total losses in the cable (Maximum)- kW component = 1.381
Total dielectric losses in the cable- Watt component = 3.3
Total sheath loss in the cable- Watt component = 13.5
Sending end power factor = 0.861
Sending end voltage (L-L) in kV = 3.312
Calculated RMS current based on LF & FF in Amperes = 42.8
Maximum load current in Amperes = 61.0

Generated from Elect 7.05

TABLE-1

COPPER CABLE PROPERTIES AT 20.0°C AND 50.0Hz FREQUENCY

Sl. No.	Cable CSA in mm²	Current Cap. in Amps.	R per km in Ohms	Xl per km in Ohms	C per km in MFD	Xc per km in k.Ohms	Impedance per km in Ohms
1	1.5	17	11.77	0.214	0.165	19.2915	11.7719
2	2.5	24	7.118	0.204	0.18	17.6839	7.1209
3	4	30	4.596	0.17	0.2	15.9155	4.5991
4	6	39	2.942	0.125	0.22	14.4686	2.9447
5	10	52	1.693	0.105	0.25	12.7324	1.6963
6	16	66	1.149	0.095	0.28	11.3682	1.1529
7	25	90	0.6614	0.086	0.385	8.2678	0.667
8	35	110	0.5309	0.083	0.42	7.5788	0.5373
9	50	135	0.378	0.08	0.46	6.9198	0.3864
10	70	165	0.2441	0.074	0.5	6.3662	0.2551
11	95	200	0.1959	0.072	0.535	5.9497	0.2087
12	120	230	0.1483	0.07	0.565	5.6338	0.164
13	150	265	0.1254	0.069	0.595	5.3497	0.1431
14	185	305	0.1007	0.0681	0.625	5.093	0.1216
15	225	340	0.091	0.067	0.655	4.8597	0.113
16	240	355	0.0769	0.0665	0.665	4.7866	0.1017
17	300	400	0.0611	0.066	0.7	4.5473	0.0899
18	400	455	0.0424	0.065	0.745	4.2726	0.0776
19	500	530	0.03	0.064	0.825	3.8583	0.0707
20	625	600	0.02	0.063	0.875	3.6378	0.0661

TABLE-2

ALUMINUM CABLE PROPERTIES AT 20.0°C AND 50.0Hz FREQUENCY

Sl. No.	Cable CSA in mm²	Current Cap. in Amps.	R per km in Ohms	Xl per km in Ohms	C per km in MFD	Xc per km in k.Ohms	Impedance per km in Ohms
1	1.5	13	19.41	0.13	0.165	19.2915	19.4104
2	2.5	18	11.75	0.125	0.18	17.6839	11.7507
3	4	23	7.585	0.123	0.2	15.9155	7.586
4	6	30	4.854	0.121	0.22	14.4686	4.8555
5	10	40	3.019	0.118	0.25	12.7324	3.0213
6	16	51	1.914	0.115	0.28	11.3682	1.9175
7	25	70	1.102	0.113	0.385	8.2678	1.1078
8	35	86	0.8849	0.11	0.42	7.5788	0.8917
9	50	105	0.6299	0.104	0.46	6.9198	0.6384
10	70	130	0.4068	0.097	0.5	6.3662	0.4182
11	95	155	0.3265	0.097	0.535	5.9497	0.3406
12	120	180	0.2471	0.0941	0.565	5.6338	0.2644
13	150	205	0.209	0.091	0.595	5.3497	0.228
14	185	240	0.1678	0.0901	0.625	5.093	0.1905
15	225	270	0.1337	0.088	0.655	4.8597	0.1601
16	240	280	0.1165	0.086	0.665	4.7866	0.1448
17	300	315	0.1018	0.086	0.7	4.5473	0.1333
18	400	375	0.0707	0.083	0.745	4.2726	0.109
19	500	430	0.0583	0.0791	0.825	3.8583	0.0983
20	625	480	0.0509	0.077	0.875	3.6378	0.0923

DEFAULT DATA OF ACSR CONDUCTORS **TABLE-3**

S.N.	Conductor	Eq. Cu mm²	Eq. Al mm²	CCC Amps	Dia. in mm	r/km ohm	xl/km ohm	Wt/km (kg)	UTS in kg	Remarks
1	SQUIRREL	13	21	75	6.33	1.374	0.355	85	756	
2	GOPHER	16	26	80	7.08	1.09	0.349	106	952	
3	WEASEL	20	31	94	7.78	0.912	0.345	128	1106	
4	FERRET	25	42	136	9	0.672	0.339	171	1503	
5	RABBIT	30	52	156	10.05	0.545	0.335	214	1813	
6	MINK	40	62	167	10.98	0.457	0.333	255	2207	
7	BEAVER	45	73	186	11.98	0.391	0.33	303	2613	
8	RACOON	48	78	204	12.27	0.366	0.329	319	2675	
9	CAT	55	95	226	13.56	0.315	0.327	385	2982	
10	DOG	65	105	240	14.15	0.275	0.315	394	3215	
11	TIGER	80	128	295	16.52	0.222	0.282	604	5790	
12	WOLF	95	154	335	18.13	0.184	0.266	726	6720	
13	LYNX	110	183	360	19.54	0.155	0.261	844	7950	
14	PANTHER	130	207	400	21	0.138	0.256	974	8934	
15	LION	140	233	430	22.26	0.122	0.252	1097	10210	
16	BEAR	160	258	470	23.46	0.11	0.25	1217	11310	
17	GOAT	185	317	525	25.96	0.09	0.244	1492	13780	
18	SHEEP	225	366	550	27.94	0.078	0.24	1726	15910	
19	DEER	260	419	630	29.9	0.068	0.237	1977	18230	
20	ELK	300	477	670	31.5	0.061	0.235	2196	20240	

CALCULATED DATA OF ACSR CONDUCTORS **TABLE-4**

S.N.	Conductor	Eq. Cu mm²	Eq. Al mm²	CCC Amps	Dia. in mm	r/km ohm	xl/km ohm	Wt/km (kg)	UTS in kg	Remarks
1	SQUIRREL	13	22	74	6.33	1.326	0.3549	85	741	
2	GOPHER	16	27	85	7.08	1.06	0.3479	106	927	
3	WEASEL	20	33	97	7.77	0.88	0.3421	128	1117	
4	FERRET	25	44	119	9	0.656	0.3328	172	1499	
5	RABBIT	30	55	141	10.05	0.526	0.3259	214	1869	
6	MINK	40	65	163	10.98	0.441	0.3203	256	2230	
7	BEAVER	45	77	188	11.97	0.371	0.3149	304	2651	
8	RACOON	48	81	196	12.27	0.353	0.3133	319	2785	
9	CAT	55	98	231	13.5	0.292	0.3073	386	3372	
10	DOG	65	108	249	14.16	0.267	0.3043	394	3303	
11	TIGER	80	137	288	16.52	0.209	0.2947	600	5809	
12	WOLF	95	165	320	18.13	0.174	0.2888	723	6997	
13	LYNX	110	192	350	19.53	0.15	0.2841	838	8119	
14	PANTHER	130	222	385	21	0.13	0.2796	969	9387	
15	LION	140	249	416	22.26	0.115	0.2759	1089	10547	
16	BEAR	160	276	448	23.45	0.104	0.2726	1209	11705	
17	GOAT	185	339	520	25.97	0.085	0.2662	1483	14356	
18	SHEEP	225	392	581	27.93	0.073	0.2617	1715	16605	
19	DEER	260	449	646	29.89	0.064	0.2574	1964	19017	
20	ELK	300	498	703	31.5	0.058	0.2541	2181	21121	

DEFAULT DATA OF AAAC CONDUCTORS **TABLE-5**

S.N.	Conductor	Eq. Cu mm²	Eq. Al mm²	CCC Amps	Dia. in mm	r/km ohm	xl/km ohm	Wt/km (kg)	UTS in kg	Remarks
1	AAAC7/2.00	14	22	103	6	1.541	0.3583	60	657	
2	AAAC7/2.50	21	34	137	7.5	0.99	0.3443	94	1031	
3	AAAC7/315	34	55	188	9.45	0.621	0.3298	149	1634	
4	AAAC7/381	50	80	240	11.43	0.425	0.3178	218	2386	
5	AAAC7/426	63	100	278	12.78	0.339	0.3108	273	2983	
6	AAAC19/289	78	125	321	14.45	0.274	0.3031	343	3735	
7	AAAC19/315	93	148	359	15.75	0.229	0.2977	407	4434	
8	AAAC19/340	108	173	397	17	0.197	0.2929	474	5152	
9	AAAC19/366	125	200	437	18.3	0.171	0.2882	549	5980	
10	AAAC19/394	145	232	481	19.7	0.147	0.2836	637	6937	
11	AAAC37/315	180	288	554	22.05	0.118	0.2765	794	8635	
12	AAAC37/345	216	346	624	24.15	0.098	0.2708	953	10355	
13	AAAC37/371	250	400	687	25.97	0.083	0.2662	1102	11967	
14	AAAC37/400	291	465	757	28	0.073	0.2615	1281	13902	
15	AAAC61/331	328	525	820	29.79	0.065	0.2576	1448	14886	
16	AAAC61/345	356	570	865	31.05	0.06	0.255	1574	16173	
17	AAAC61/355	378	604	899	31.95	0.057	0.2532	1666	17124	
18	AAAC61/366	401	642	935	32.94	0.053	0.2513	1771	18189	
19	AAAC61/381	434	695	985	34.29	0.049	0.2488	1919	19699	
20	AAAC61/400	479	767	1050	36	0.045	0.2457	2116	21714	

CALCULATED DATA OF AAAC CONDUCTORS **TABLE-6**

S.N.	Conductor	Eq. Cu mm²	Eq. Al mm²	CCC Amps	Dia. in mm	r/km ohm	xl/km ohm	Wt/km (kg)	UTS in kg	Remarks
1	AAAC7/2.00	14	22	106	6	1.547	0.3583	60	658	
2	AAAC7/2.50	21	34	135	7.5	0.99	0.3443	94	1029	
3	AAAC7/315	34	55	182	9.45	0.624	0.3298	149	1633	
4	AAAC7/381	50	80	241	11.43	0.426	0.3178	219	2389	
5	AAAC7/426	63	100	288	12.78	0.341	0.3108	273	2987	
6	AAAC19/289	78	125	337	14.45	0.273	0.3031	341	3732	
7	AAAC19/315	93	148	368	15.75	0.23	0.2977	406	4433	
8	AAAC19/340	108	173	401	17	0.197	0.2929	473	5165	
9	AAAC19/366	125	200	438	18.3	0.17	0.2882	548	5985	
10	AAAC19/394	145	232	480	19.7	0.147	0.2836	635	6936	
11	AAAC37/315	180	288	580	22.05	0.118	0.2765	790	8633	
12	AAAC37/345	216	346	632	24.15	0.098	0.2708	948	10356	
13	AAAC37/371	250	400	681	25.97	0.085	0.2662	1096	11975	
14	AAAC37/400	291	465	740	28	0.073	0.2615	1274	13921	
15	AAAC61/331	328	525	823	29.79	0.065	0.2576	1438	15715	
16	AAAC61/345	356	570	858	31.05	0.06	0.255	1562	17073	
17	AAAC61/355	378	604	883	31.95	0.056	0.2532	1654	18077	
18	AAAC61/366	401	642	912	32.94	0.053	0.2513	1758	19215	
19	AAAC61/381	434	695	953	34.29	0.049	0.2488	1906	20822	
20	AAAC61/400	479	767	1008	36	0.044	0.2457	2100	22950	

USER DATA OF AAC CONDUCTORS **TABLE-7**

S.N.	Conductor	Eq. Cu mm²	Eq. Al mm²	CCC Amps	Dia. in mm	r/km ohm	xl/km ohm	Wt/km (kg)	UTS in kg	Remarks
1	Conops	13	21	100	6.454	1.359	0.3537	58	363	
2	Gnat	16	26	116	6.63	1.09	0.352	72	444	
3	Weevil	20	31	129	7.874	0.913	0.3412	86	521	
4	LadyBird	25	42	159	8.37	0.672	0.3374	117	737	
5	Ant	30	52	182	9.3	0.544	0.3308	144	892	
6	Fly	40	63	207	10.198	0.453	0.325	174	1051	
7	BlueBottle	45	73	225	10.978	0.391	0.3203	201	1203	
8	GrassHopper	50	83	250	11.728	0.344	0.3162	230	1356	
9	Cleg	60	95	270	12.508	0.301	0.3121	261	1523	
10	Wasp	65	105	292	13.168	0.272	0.3089	290	1673	
11	AAC 11	80	132	335	14.79	0.215	0.3016	369	2228	
12	Peony	95	149	363	15.676	0.192	0.298	414	2484	
13	Caterpillar	110	183	420	17.402	0.156	0.2914	511	2985	
14	Chafer	130	210	460	18.636	0.136	0.2871	586	3381	
15	AAC 15	140	234	495	19.67	0.122	0.2837	652	3736	
16	AAC 16	160	262	530	20.802	0.109	0.2802	730	4144	
17	AAC 17	185	318	600	22.92	0.09	0.2741	886	4947	
18	AAC 18	225	367	654	24.65	0.078	0.2695	1025	5695	
19	AAC 19	300	474	764	27.994	0.06	0.2615	1343	7289	
20	Scorpion	325	518	805	29.288	0.055	0.2587	1464	7878	

USER DATA OF ACSR CONDUCTORS **TABLE-8**

S.N.	Conductor	Eq. Cu mm²	Eq. Al mm²	CCC Amps	Dia. in mm	r/km ohm	xl/km ohm	Wt/km (kg)	UTS in kg	Remarks
1	Squirrel	13	21	75	6.32	1.374	0.355	85	771	
2	Gopher	16	26	80	7.08	1.09	0.349	106	952	
3	Weasel	20	31	94	7.78	0.917	0.345	125	1136	
4	Ferret	25	42	136	9	0.672	0.339	171	1503	
5	Rabbit	30	52	156	10.06	0.545	0.335	214	1860	
6	Mink	40	62	167	10.98	0.457	0.333	255	2207	
7	Beaver	45	73	186	11.98	0.391	0.33	303	2613	
8	Racoon	48	78	204	12.28	0.366	0.329	318	2746	
9	Cat	55	95	226	13.56	0.315	0.327	385	3324	
10	Dog	65	104	240	14.16	0.275	0.315	394	3899	
11	Tiger	80	128	295	16.52	0.222	0.282	604	5790	
12	Wolf	95	154	335	18.14	0.184	0.266	727	7350	
13	Lynx	110	183	360	19.54	0.155	0.261	844	7950	
14	Panther	130	207	400	21	0.138	0.256	976	9127	
15	Lion	140	233	430	22.26	0.122	0.252	1097	10210	
16	Bear	160	258	470	23.46	0.11	0.25	1217	11310	
17	Goat	185	317	525	25.96	0.09	0.244	1492	13780	
18	Sheep	225	336	550	27.94	0.077	0.24	1726	15910	
19	Deer	260	419	630	29.9	0.068	0.237	1977	18230	
20	Elk	300	477	670	31.5	0.061	0.235	2196	20240	

PHYSICAL COSTANTS OF CALCULATING ACSR DATA **TABLE - 9**

SL.NO.	*C O N S T A N T S*	*VALUE*
1	Specific gravity of Aluminium	2.703
2	Specific gravity of Steel	7.85
3	Ultimate Tensile strength of Aluminium in kg/mm²	13
4	Ultimate Tensile strength of Al Alloy in kg/mm²	29.9
5	Ultimate Tensile strength of Steel in kg/mm²	143
6	Electrical Resistivity of Copper ohm mm²/km	17.86
7	Electrical Resistivity of Aluminium ohm mm²/km	28.7
8	Electrical Resistivity of Steel ohm mm²/km	150
9	Permittivity of free space	8.8x10^(-12)
10	Normal Temperature in °C	20
11	Equiv.spacing between conductors in mm	700

PHYSICAL COSTANTS OF CALCULATING AAAC DATA **TABLE - 10**

SL.NO.	*C O N S T A N T S*	*VALUE*
1	Specific gravity of Aluminium	2.703
2	Specific gravity of Steel	7.85
3	Ultimate Tensile strength of Aluminium in kg/mm²	13
4	Ultimate Tensile strength of Al Alloy in kg/mm²	29.9
5	Ultimate Tensile strength of Steel in kg/mm²	143
6	Electrical Resistivity of Copper ohm mm²/km	17.86
7	Electrical Resistivity of Aluminium ohm mm²/km	28.7
8	Electrical Resistivity of Steel ohm mm²/km	150
9	Permittivity of free space	8.8x10^(-12)
10	Normal Temperature in °C	20
11	Equiv.spacing between conductors in mm	700

COSTING OF 3-PHASE POWER CABLES

A series of cost of different voltage grades, insulations, conductors etc. are collected from various reliable sources and the prevailing market on a base date of September 2003. The following categories are then constituted for group generalization:

1. Voltage (650/1100, 3300, 6600, 11000 and 33000V)
2. Conductor (Copper and Aluminium)
3. Armouring (Armoured and Unarmoured)
4. Number of Cores (3, 3½ and 4)
5. Insulation (PVC, XLPE and PILC)

Based on the data collected the following graphs were drawn between cross sectional area (csa) in sq.mm. and unit cost of cable in Rs. '000. The graphs are enclosed with this text for ready reference:

A. 1100V, Al, Unarmoured, 3-Core and PVC insulation cables
B. 1100V, Al, Armoured, 3-Core and PVC insulation cables
C. 3300V, Al, Armoured, 3-Core and PVC insulation cables
D. 3300V, Al, Armoured, 3-Core and XLPE insulation cables
E. 3300V, Cu, Armoured, 3-Core and PVC insulation cables
F. 3300V, Al, Armoured, 3-Core and PILC insulation cables
G. 6600V, Al, Armoured, 3-Core and XLPE insulation cables
H. 6600V, Al, Armoured, 3-Core and PILC insulation cables
I. 6600V, Cu, Armoured, 3-Core and PVC insulation cables
J. 11000V, Al, Armoured, 3-Core and PVC insulation cables
K. 11000V, Al, Armoured, 3-Core and XLPE insulation cables
L. 11000V, Al, Armoured, 3-Core and PILC insulation cables
M. 11000V, Cu, Armoured, 3-Core and PVC insulation cables
N. 33000V, Al, Armoured, 3-Core and XLPE insulation cables

The trends of variation of costs with the cross sectional areas, csa, of cable/km are then obtained and are shown in the following table:

Sl. No.	Voltage Grade	Core	Arm-ouring	Cond-uctor	Insulation	Trend Equation	Basis
A	1100	3	U	Al	PVC	$cpkm = 1.42 \times a + 22$	PMP
B	1100	3	A	Al	PVC	$cpkm = 1.45 \times a + 35$	PMP
C	3300	3	A	Al	PVC	$cpkm = 2.95 \times a + 75$	PMP
D	3300	3	A	Al	XLPE	$cpkm = 3.82 \times a + 315$	PMP
E	3300	3	A	Cu	PVC	$cpkm = 5.54 \times a + 80$	PMP
F	3300	3	A	Cu	PILC	Abnormal curve	PMP
G	6600	3	A	Al	XLPE	$cpkm = 4.14 \times a + 338$	PMP
H	6600	3	A	Al	PILC	$cpkm = 4.64 \times a + 338$	PMP
I	6600	3	A	Cu	PVC	$cpkm = 7.36 \times a + 320$	PMP
J	11000	3	A	Al	PVC	$cpkm = 4.32 \times a + 524$	PMP
K	11000	3	A	Al	XLPE	$cpkm = 4.91 \times a + 524$	PMP
L	11000	3	A	Al	PILC	$cpkm = 7.92 \times a + 594$	PMP
M	11000	3	A	Cu	PVC	Much deviated figures are obtained	PMP
N	33000	3	A	Al	XLPE	$cpkm = 5.3875 \times a + 1040$	PMP

PMP – Prevailing Market Price   A- Armoured   U- Unarmoured   Al- AluminiumCu- Copper

To start with, we find the difference of cost between copper and aluminium conductors for a three phase cable with different cross sections. The method by which this difference in cost cd is obtained is given hereunder in the table:

COST DIFFERENCE BETWEEN Cu & Al

Sl. No.	Cable CS Area sq.mm.	VOLUME in litre	Wt. of Al in kg	Wt. of Cu in kg	Cost of Al in Rs. '000	Cost of Cu in Rs. '000	Cost Diff. in Rs. '000
			2.703	8.93			
1	1.5	4.5	12	40	1.5	8.0	6.6
2	2.5	7.5	20	67	2	13	11.0
3	4	12	32	107	4	21	18
4	6	18	49	161	6	32	26
5	10	30	81	268	10	54	44
6	16	48	130	429	16	86	70
7	25	75	203	670	24	134	110
8	35	105	284	938	34	188	153
9	50	150	405	1340	49	268	219
10	70	210	568	1875	68	375	307
11	95	285	770	2545	92	509	417
12	120	360	973	3215	117	643	526
13	150	450	1216	4019	146	804	658
14	185	555	1500	4956	180	991	811
15	225	675	1825	6028	219	1206	987
16	240	720	1946	6430	234	1286	1052
17	300	900	2433	8037	292	1607	1315
18	400	1200	3244	10716	389	2143	1754
19	500	1500	4055	13395	487	2679	2192
20	625	1875	5068	16744	608	3349	2741

EMPIRICAL FORMULAE FOR COSTING OF
3-CORE POWER CABLES

Referring to foregoing equations, derived on the basis of the trend of prevailing market price as on 1st September 2003 and the difference of cost between copper and aluminium conductors, the following equations are set for the different types and category of power cables:

S. N.	Volt-age	Armo-uoring	Co res	Cond-uctor	Insul-ation	Empirical Equation	Basis
1	1100	U	3	Al	PVC	$cpkm = 1.42 \times \quad + 22$	PMP
2					XLPE	$cpkm = 1.37 \times (1.42 \times a + 22)$	D
3				Cu	PVC	$cpkm = 1.42 \times \quad + 22 + cd$	D
4					XLPE	$cpkm = 1.37 \times (1.42 \times a + 22 + cd)$	D
5		A	3	Al	PVC	$cpkm = 1.45 \times a + 35$	PMP
6					XLPE	$cpkm = 1.37 \times (1.45 \times a + 35)$	D
7				Cu	PVC	$cpkm = 1.45 \times a + 35 + cd$	D
8					XLPE	$cpkm = 1.37 \times (1.45 \times a + 35 + cd)$	D
9	3300	A	3	Al	PVC	$cpkm = 2.95 \times \quad + 75$	PMP
10					XLPE	$cpkm = 3.82 \quad a + 315$	PMP
11					PILC	$cpkm = 4.32 \times a + 315$	D
12				Cu	PVC	$cpkm = 5.54 \times \quad + 80$	PMP
13					XLPE	$cpkm = 3.82 \times a + 315 + cd$	D
14					PILC	$cpkm = 4.32 \times a + 315 + cd$	D
15	6600	A	3	Al	PVC	$cpkm = 7.36 \times a \quad 320 - cd$	D
16					XLPE	$cpkm = 4.14 \times a + 338$	PMP
17					PILC	$cpkm = 4.64 \times a + 338$	PMP
18				Cu	PVC	$cpkm = 7.36 \times a + 320$	PMP
19					XLPE	$cpkm = 4.14 \times a \quad 338 + cd$	D
20					PILC	$cpkm = 4.64 \times a + 338 + cd$	D
21	11000	A	3	Al	PVC	$cpkm = 4.32 \times a + 524$	PMP

S. N.	Volt-age	Armo-uoring	Co res	Cond-uctor	Insul-ation	Empirical Equation	Basis
22					XLPE	$cpkm = 4.91 \times a + 524$	PMP
23					PILC	$cpkm = 7.92 \times a + 594$	PMP
24				Cu	PVC	$cpkm = 4.32 \times \quad + 524 + cd$	D
25					XLPE	$cpkm = 4.91 \times a + 524 + cd$	D
26					PILC	$cpkm = 7.92 \times a + 594 + cd$	D
27	33000	A	3	Al	XLPE	$cpkm = 5.3875 \times a + 1040$	PMP
28				Cu	XLPE	$cpkm = 5.3875 \times a + 1040 + cd$	D

Abbrv.: cd- Cost Difference (Cu-Al) cpkm– Cost/km in Rs. '000 a- csa in sq.mm. D- Derived

POWER CABLES OF 3½ and 4-CORES

The cost per km of cables of 3½ and 4 core cables of different voltages, conductors and insulations have been directly derived on the basis as under:

Cost of 3½ Core Cable = 1.10 x Cost of 3 Core Cable
Cost of 4 Core Cable = 1.20 x Cost of 3 Core Cable

COSTING OF OVERHEAD LINES

Overhead Line is not a single entity. Moreover, each entity of it has number of different values. So, costing of overhead lines has to consider a number of factors involved and affecting the present cost. In the following para, an effort has been made to arrive at a very close estimate for the cost of a given overhead line of any possible specification.

*The major **entities** of overhead lines are as under:*

1. Working Voltage
2. Insulators
3. Type of Circuit
4. Type of Conductor
5. Conductor
6. Earth Conductor
7. Type of Structure & Heights
8. Earthing
9. Ruling Span
10. Date of estimate

1. WORKING VOLTAGE

The following working voltages have been considered in the cost estimation:

a. 415 V
b. 550 V
c. 3300 V
d. 6600 V
e. 11000 V
f. 33000 V
g. 132000 V
h. 220000 V

2. INSULATORS

The following types of Insulators have been considered in the cost estimation:

a. Pin type LT Insulator
b. Pin type HT Insulator
c. 11000V Disc type Insulator

For 415V and 550V only Pin type LT Insulator has been considered in costing, while for 3300V and 6600V Pin type HT Insulator has been considered for costing. For 11000V and above only 11kV Disc type Insulators have been considered. Numbers of 11kV Insulators in series are taken as under:

a. 33000 V - Each string of 3x11000V
b. 132000 V – Each string of 12x11000V
c. 220000 V – Each string of 20x11000V

3. TYPE OF CIRCUIT

The following types of circuits have been considered in the cost estimation:

a. Single Circuit – Each phase having 1 conductor i.e. 3-Conductors
b. Double Circuit - Each phase having 2 conductors i.e. 6-Conductors

4. TYPE OF CONDUCTOR

The following types of Conductors have been considered in the cost estimation:

a. ACSR Conductor (Aluminium Conductor Steel Reinforced)
b. AAAC Conductor (All Aluminium Alloy Conductor)

It is to be noted that cost of conductor is proportional to volume or weight of Aluminium/ Steel. This may be inferred from above that cost of conductor is proportional to equivalent Aluminium cross sectional area of the types of conductors.

5. CONDUCTOR

Series of 20 commonly used conductors in each type have been considered in the cost estimation. The list of each series is as under:

ACSR	Eqv. Al Area in sq. mm.	AAAC	Eqv. Al Area in sq. mm.
SQUIRREL	21	AAAC7/2.00	22
GOPHER	26	AAAC7/2.50	34
WEASEL	31	AAAC7/3.15	55
FERRET	42	AAAC7/3.81	80
RABBIT	52	AAAC7/4.26	100
MINK	62	AAAC19/2.89	125
BEAVER	73	AAAC19/3.15	148
RACOON	78	AAAC19/3.40	173
CAT	95	AAAC19/3.66	200
DOG	105	AAAC19/3.94	232
TIGER	128	AAAC37/3.15	288
WOLF	154	AAAC37/3.45	346
LYNX	183	AAAC37/3.71	400
PANTHER	207	AAAC37/4.00	465
LION	233	AAAC61/3.31	525
BEAR	258	AAAC61/3.45	570
GOAT	317	AAAC61/3.55	604
SHEEP	366	AAAC61/3.66	642
DEER	419	AAAC61/3.81	695
ELK	477	AAAC61/4.00	767

The names of the AAAC series indicate the diameter of the wire used in stranding of the conductor as per Indian Standards.

6. EARTH CONDUCTOR

The following types of Earth Conductor of material Galvanized Steel Wire have been considered in the cost estimation:

1. 1x3.15 mm diameter – for 415V and 550V.
2. 7x2.59 mm diameter – for 3.3kV, 6.6kV and 11kV
3. 7x3.15 mm diameter – for 33kV
4. 7x3.55 mm diameter – 132kv and 220kV

7. TYPE OF STRUCTURES & THEIR HEIGHTS

The following types of structure for carrying the conductor and other accessories have been considered in the cost estimation:

a.	Steel Tubular Poles (25kg/m)	Hts: 8, 9, 10, 11, 12, 13 and 16m
b.	PCC Poles (400kg)	Hts: 8(S), 9(S), 9.5(Virendeel), 9.5(S)m
c.	Rail Poles (52kg/m)	Hts: 9, 9.5, 10, 11, 12, 13 and 15m
d.	Tower Structures	Hts: 12m – 36m @ 3m Extension

8. EARTHING

The ELECT program has considered 2 earth points per km of overhead line.

9. RULING SPAN

Ruling Span has been defined at page no. 38 of the 'Technology behind Elect'. The range of Ruling Span may be set any value between 5m and 500m.

10. DATE OF ESTIMATE

This is again an important factor. Care has been taken for the overall cost escalation of overhead line. An average monthly escalation of 0.5% has been considered for this factor.

ESTIMATING INDIVIDUAL COSTS OF OHL ITEMS:

Cost of overhead line shall be calculated on per km basis. For this, rates of various conductors, earth conductors, poles/ towers, insulators with hardware, clamps/ brackets are to be set as on a base date.

This program has set base date as ***1st September 2003***. All basic rates are referred to that date.

The different items whose costs are to be estimated are as under:

a. CONDUCTOR COST
b. EARTH WIRE COST

c. STRUCTURE COST
d. INSULATOR & HARDWARE COST
e. BRACKETS/ CLAMPS ETC. COST
f. PCC WORK AT POLES
g. EARTHING COST
h. TRANSPORATATION, ERECTION & SUPERVISION ETC.

a. CONDUCTOR COST

Conductor cost Index has been set corresponding to the base date as:

Conductor Cost Index **k** = **2000**

The use and method of finding this value of conductor cost index has been widely elaborated within the *Elect* program on the basis of the theory discussed at pages 12 to 15 of the 'Technology behind Elect'. The conductor cost is given by:

Cost = Index x Aluminium Area x No. of circuits x Escalation factor

Where Escalation factor = 1+ Rate Esc. x months passed

b. EARTHWIRE COST

The basic cost of 7x3.15 mm. GI wire is set at Rs. 25000/= per km. Cost of other combination of wires have been derived from this value as under

i. 1x3.15 mm GI wire - 0.15 of Rs. 25000/= per km
ii. 7x2.59 mm GI wire - 0.67 of Rs. 25000/= per km
iii. 7x3.55 mm GI wire - 1.27 of Rs. 25000/= per km

c. STRUCTURE COST

Basic height-wise structure cost as on base date have been taken as under:

Ht. Index	STEEL TUBULAR POLE	PCC POLE	RAIL POLE	TOWER	
	COST	COST	COST	COST	BASE in m
0	4500	1600	15000	60000	2.6x2.6
1	5400	3300	17000	80000	3.5x3.5
2	8200	3000	19000	100000	4.2x4.2
3	11600	3500	23000	120000	5x5
4	14800	-	27000	142000	5.5x5.8
5	17400	-	31000	162000	6.7x6.7
6	21000	-	39000	180000	7.5x7.5
7	-	-	-	205000	8.4x8.4
8	-	-	-	225000	9.3x9.3

Number of structures per km is arrived at with the help of selected 'SPAN' of the overhead line.

No. of Structures = 1000/ Span

Where 1000m is unit length of Overhead line and
Span is Ruling Span in metres

It is to be noted that the above relation may not always yield a whole number. It is always better to estimate on a bit higher side than actual. In view of this, the above value of number of structures should be rounded off on the higher side, if obtained in fraction.

d. INSULATOR & HARDWARE COST

Basic costs of insulators are as under:

1. LT Pin type @ Rs. 110/= per piece
2. HT Pin type @ Rs. 250/= per piece
3. 11kV Disc type @ Rs. 400/= per piece
4. Hardware for Disc type @ Rs. 500/= per set

Empirical formulae for insulator costs are as under:

For PIN Type Insulators:

Unit Rate of Pin Insulator = Base Rate x Esc.
Cost = Unit Rate x Insulators/km

For DISC Type Insulators:

Cost = (Insulators/km x Rate + No. of Strings x 3 x Circuits x Rate of HW) x Esc.

Where Esc = 1+ Rate of Escalation x months passed and
Insulators/km = No. of Spans x 3 x Circuits x (kV/11) for 11kV and above

e. BRACKETS/ CLAMPS ETC. COST

Cost of brackets, angles, clamps etc. depend on number of bracket sets and weight of structure. Weight of structure in turn depends on weight of pole/ tower, insulators and conductors.

The program for costing of brackets has used the following empirical formula:

Cost = Bracket sets x Cost of (Structure + Insulator + Conductor) x 0.0015

f. COST OF PCC WORK AT POLES/ TOWERS

Cost of Cement Concrete Work depends on number of working points and weight of structure. Weight of structure in turn depends on weight of pole/ tower, insulators and conductors.

The program for costing of PCC has used the following empirical formula:

Cost = Pole/km x Cost of (Structure + Insulator + Conductor) x 0.0025

g. EARTHING COST

As already stated, 2 earth points have been envisaged per km of overhead line in this program. Cost of two earth pits at suitable pole/ tower legs are estimated as equal to 10% of the cost of earth conductor/km and is given by the empirical relation as under:

Cost = Cost of Earth Conductor x 0.125

h. TRANSPORATATION, ERECTION & SUPERVISION ETC. COST

Transportation of structure and other materials, stringing of insulators, drawing of conductors, earth wires etc. along with supervision of the entire work is taken as 25% of the overall cost of all materials.

COST OF OVERHEAD LINE:

Summing up the above estimated values of different items of overhead line, including the supervision and installation charges, it may concluded as under:

Cost of OHL = Conductor Cost + Earth wire Cost + Structure Cost
+ Insulators & Hardware Cost + Brackets/ Clamps etc. Cost
+ PCC Work Cost + Earthing Cost
+ Supervision/ Transportation/ Erection etc.