A4

Equivalent Circuits and Parameters of Power System Plant

Network Protection & Automation Guide

Life Is On | Schneider Electric

Chapter

A4

Equivalent Circuits and Parameters of Power System Plant

1. Introduction

Knowledge of the behaviour of the principal electrical system plant items under normal and fault conditions is a prerequisite for the proper application of protection. This chapter summarises basic synchronous machine, transformer and transmission line theory and gives equivalent circuits and parameters so that a fault study can be successfully completed before the selection and application of the protection systems described in later chapters. Only what might be referred to as 'traditional' synchronous machine theory is covered, as that is all that calculations for fault level studies generally require. Readers interested in more advanced models of synchronous machines are referred to the numerous papers on the subject, of which [Ref A4.1: Physical significance of sub-subtransient quantities in dynamic behaviour of synchronous machines] is a good starting point.

Power system plant may be divided into two broad groups - static and rotating.

The modelling of static plant for fault level calculations provides few difficulties, as plant parameters generally do not change during the period of interest following fault inception. The problem in modelling rotating plant is that the parameters change depending on the response to a change in power system conditions.

2. Synchronous machines

There are two main types of synchronous machine: cylindrical rotor and salient pole. In general, the former is confined to 2 and 4 pole turbine generators, while salient pole types are built with 4 poles upwards and include most classes of duty. Both classes of machine are similar in so far that each has a stator carrying a three-phase winding distributed over its inner periphery. Within the stator bore is carried the rotor which is magnetised by a winding carrying d.c. current.

The essential difference between the two classes of machine lies in the rotor construction. The cylindrical rotor type has a uniformly cylindrical rotor that carries its excitation winding distributed over a number of slots around its periphery. This construction is unsuited to multi-polar machines but it is very sound mechanically. Hence it is particularly well adapted for the highest speed electrical machines and is universally employed for 2 pole units, plus some 4 pole units.

The salient pole type has poles that are physically separate, each carrying a concentrated excitation winding. This type of construction is in many ways complementary to that of the cylindrical rotor and is employed in machines having 4 poles or more. Except in special cases its use is exclusive in machines having more than 6 poles. Figure A4.1 illustrates a typical large cylindrical rotor generator installed in a power plant.

Two and four pole generators are most often used in applications where steam or gas turbines are used as the driver. This is because the steam turbine tends to be suited to high rotational speeds. Four pole steam turbine generators are most often found in nuclear power stations as the relative wetness of the steam makes the high rotational speed of a two-pole design unsuitable. Most generators with gas turbine drivers are four pole machines to obtain enhanced mechanical strength in the rotor, since a gearbox is often used to couple the power turbine to the generator, the choice of synchronous

Figure A4.1:
Large synchronous generator

speed of the generator is not subject to the same constraints as with steam turbines.

Generators with diesel engine drivers are invariably of four or more pole design, to match the running speed of the driver without using a gearbox. Four-stroke diesel engines usually have a higher running speed than two-stroke engines, so generators having four or six poles are most common. Two-stroke diesel engines are often derivatives of marine designs with relatively large outputs (circa 30MW is possible) and may have running speeds of the order of 125rpm. This requires a generator with a large number of poles (48 for a 125rpm, 50Hz generator) and consequently is of large diameter and short axial length. This is a contrast to turbine-driven machines that are of small diameter and long axial length.

3. Armature Reaction

Armature reaction has the greatest effect on the operation of a synchronous machine with respect both to the load angle at which it operates and to the amount of excitation that it needs. The phenomenon is most easily explained by considering a simplified ideal generator with full pitch winding operating at unity p.f., zero lag p.f. and zero lead p.f. When operating at unity p.f. (power factor), the voltage and current in the stator are in phase, the stator current producing a cross magnetising magneto-motive force (m.m.f.) which interacts with that of the rotor, resulting in a distortion of flux across the pole face. As can be seen from Figure A4.2(a) the tendency is to weaken the flux at the leading edge or effectively to distort the field in a manner equivalent to a shift against the direction of rotation.

If the power factor were reduced to zero lagging, the current in the stator would reach its maximum 90° after the voltage and the rotor would therefore be in the position shown in Figure A4.2(b). The stator m.m.f. is now acting in direct opposition to the field.

Similarly, for operation at zero leading power factor, the stator m.m.f. would directly assist the rotor m.m.f. This m.m.f. arising from current flowing in the stator is known as 'armature reaction'.
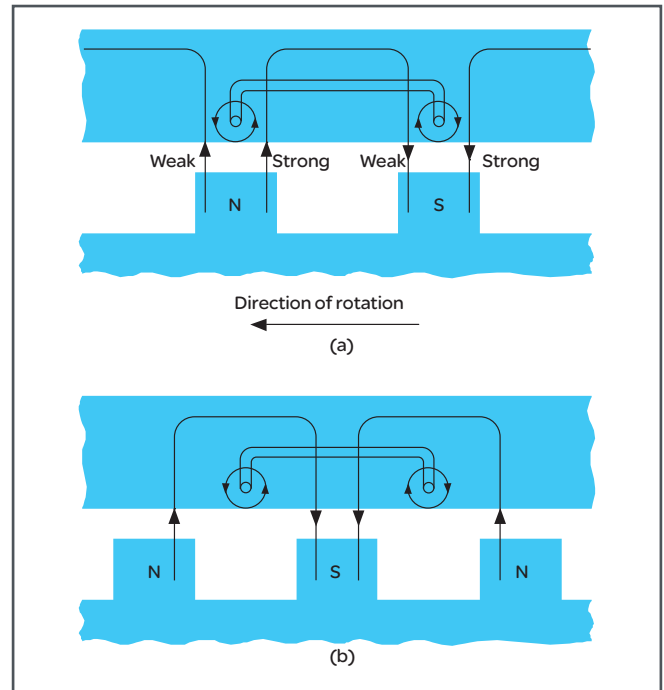

Figure A4.2:
Distortion of flux due to armature reaction

A4

4. Steady state theory

The vector diagram of a single cylindrical rotor synchronous machine is shown in Figure A4.3, assuming that the magnetic circuit is unsaturated, the air-gap is uniform and all variable quantities are sinusoidal. Further, since the reactance of machines is normally very much larger than the resistance, the latter has been neglected.
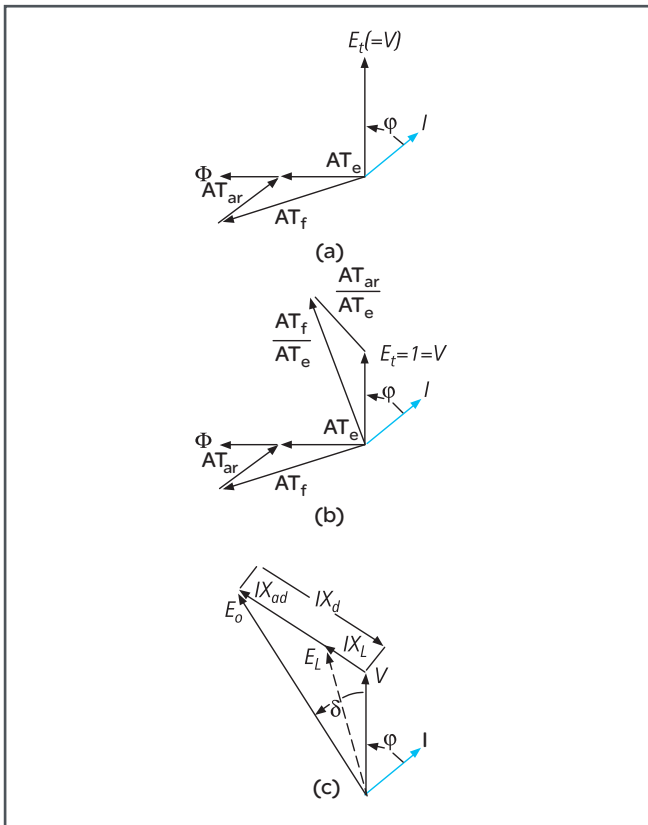

Figure A4.3:
Vector diagram of synchronous machine

The excitation ampere-turns, AT_e, produces a flux Φ across the air-gap thereby inducing a voltage, E_t, in the stator. This voltage drives a current I at a power factor $\cos^{-1}\Phi$ and gives rise to an armature reaction m.m.f. AT_{ar} in phase with it. The m.m.f. AT_f resulting from the combination of these two m.m.f. vectors (see Figure A4.3(a)) is the excitation which must be provided on the rotor to maintain flux Φ across the air-gap. Rotating the rotor m.m.f. diagram, Figure A4.3(a), clockwise until AT_e coincides with E_t and changing the scale of the diagram so that AT_e becomes the basic unit, where AT_e $=E_t=1$, results in Figure A4.3(b). The m.m.f. vectors have thus become, in effect, voltage vectors.

For example AT_{ar}/AT_e is a unit of voltage that is directly proportional to the stator load current. This vector can be fully represented by a reactance and in practice this is called 'armature reaction reactance' and is denoted by X_{ad}. Similarly, the remaining side of the triangle becomes AT_f/AT_e, which

is the per unit voltage produced on open circuit by ampere-turns AT_f. It can be considered as the internal generated voltage of the machine and is designated E_o.

The true leakage reactance of the stator winding which gives rise to a voltage drop or regulation has been neglected. This reactance is designated X_L (or X_a in some texts) and the voltage drop occurring in it, IX_L is the difference between the terminal voltage V and the voltage behind the stator leakage reactance, E_L.

IZ_L is exactly in phase with the voltage drop due to X_{ad}, as shown on the vector diagram Figure A4.3(c). It should be noted that X_{ad} and X_L can be combined to give a simple equivalent reactance; this is known as the 'synchronous reactance', denoted by X_d.

The power generated by the machine is given by the equation:

$$P = VI\cos\varphi = \frac{VE}{X_d}\sin\delta \quad \text{...Equation A4.1}$$

where δ is the angle between the internal voltage and the terminal voltage and is known as the load angle of the machine.

It follows from the above analysis that, for steady state performance, the machine may be represented by the equivalent circuit shown in Figure A4.4, where X_L is a true reactance associated with flux leakage around the stator winding and X_{ad} is a fictitious reactance, being the ratio of armature reaction and open-circuit excitation magneto-motive forces.

Figure A4.4:
Equivalent circuit of elementary machine
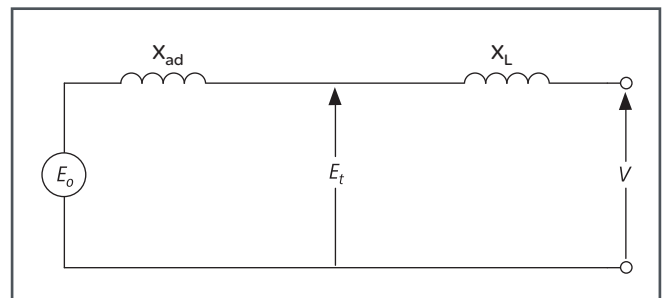
In practice, due to necessary constructional features of a cylindrical rotor to accommodate the windings, the reactance X_a is not constant irrespective of rotor position, and modelling proceeds as for a generator with a salient pole rotor. However, the numerical difference between the values of X_{ad} and X_{aq} is small, much less than for the salient pole machine.

The preceding theory is limited to the cylindrical rotor generator. The basic assumption that the air-gap is uniform is very obviously not valid when a salient pole rotor is being considered. The effect of this is that the flux produced by armature reaction m.m.f. depends on the position of the rotor at any instant, as shown in Figure A4.5.
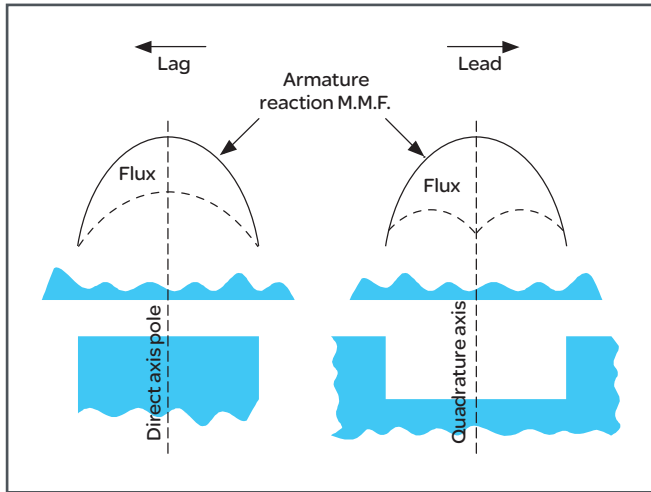
Figure A4.5:
Variation of armature reaction m.m.f. with pole position

Figure A4.6:
Vector diagram for salient pole machine

When a pole is aligned with the assumed sine wave m.m.f. set up by the stator, a corresponding sine wave flux will be set up, but when an inter-polar gap is aligned very severe distortion is caused. The difference is treated by considering these two axes, that is those corresponding to the pole and the inter-polar gap, separately. They are designated the 'direct' and 'quadrature' axes respectively, and the general theory is known as the 'two axis' theory.

The vector diagram for the salient pole machine is similar to that for the cylindrical rotor except that the reactance and currents associated with them are split into two components. The synchronous reactance for the direct axis is $X_d = X_{ad} + X_L$, while that in the quadrature axis is $X_q = X_{aq} + X_L$. The vector diagram is constructed as before but the appropriate quantities in this case are resolved along two axes. The resultant internal voltage is E_0, as shown in Figure A4.6.

In passing it should be noted that E'_0 is the internal voltage which would be given, in cylindrical rotor theory, by vectorially adding the simple vectors IX_d and V. There is very little difference in magnitude between E_0 and E'_0 but a substantial difference in internal angle; the simple theory is perfectly adequate for calculation of excitation currents but not for stability considerations where load angle is significant.

6. Transient analysis

For normal changes in load conditions, steady state theory is perfectly adequate. However, there are occasions when almost instantaneous changes are involved, such as faults or switching operations. When this happens new factors are introduced within the machine and to represent these adequately a corresponding new set of machine characteristics is required.

The generally accepted and most simple way to appreciate the meaning and derivation of these characteristics is to consider a sudden three-phase short circuit applied to a machine initially running on open circuit and excited to normal voltage E_0.

This voltage will be generated by a flux crossing the air-gap. It is not possible to confine the flux to one path exclusively in any machine, and as a result there will be a leakage flux Φ_L that will leak from pole to pole and across the inter-polar gaps without crossing the main air-gap as shown in Figure A4.7. The flux in the pole will be $\Phi + \Phi_L$.
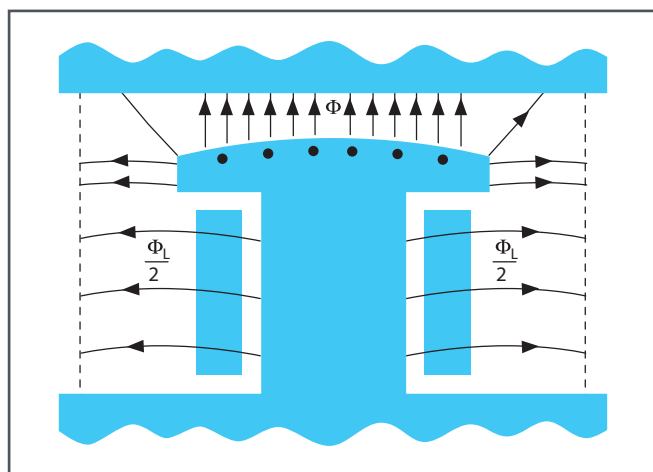
Figure A4.7:
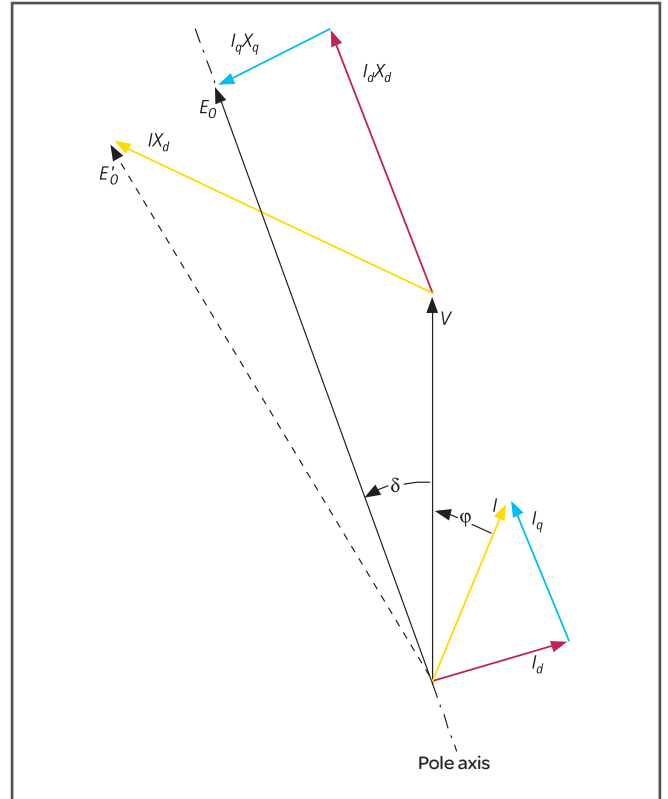**Flux paths of salient pole machine**

If the stator winding is then short-circuited, the power factor in it will be zero. A heavy current will tend to flow, as the resulting armature reaction m.m.f. is demagnetising. This will reduce the flux and conditions will settle until the armature reaction nearly balances the excitation m.m.f., the remainder maintaining a very much reduced flux across the air-gap which is just sufficient to generate the voltage necessary to overcome the stator leakage reactance (resistance neglected). This is the simple steady state case of a machine operating on short circuit and is fully represented by the equivalent of Figure A4.8(a); see also Figure A4.4.
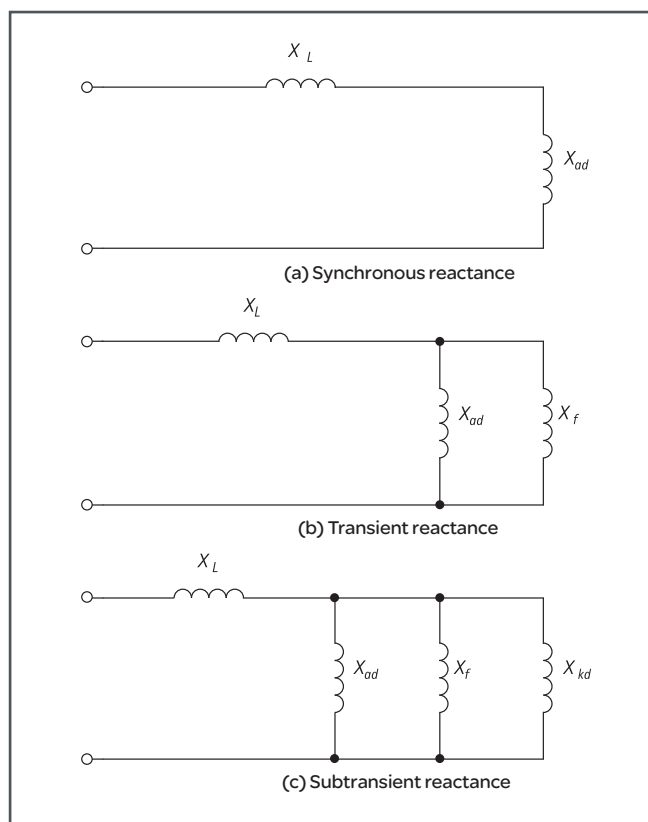
Figure A4.8:
Synchronous machine reactances

It might be expected that the fault current would be given by $E_0 / (X_L + X_{ad})$ equal to E_0 / X_d, but this is very much reduced, and the machine is operating with no saturation. For this reason, the value of voltage used is the value read from the air-gap line corresponding to normal excitation and is rather higher than the normal voltage. The steady state current is given by:

$$I_d = \frac{E_g}{X_d}$$

…Equation A4.2

where E_g = voltage on air gap line

An important point to note now is that between the initial and final conditions there has been a severe reduction of flux. The rotor carries a highly inductive winding which links the flux so that the rotor flux linkages before the short circuit are produced by $(\Phi + \Phi_L)$. In practice the leakage flux is distributed over the whole pole and all of it does not link all the winding. Φ_L is an equivalent concentrated flux imagined to link all the winding and of such a magnitude that the total linkages are equal to those actually occurring. It is a fundamental principle that any attempt to change the flux linked with such a circuit will cause current to flow in a direction that will oppose the change. In the present case the flux is being reduced and so the induced currents will tend to sustain it.

For the position immediately following the application of the short circuit, it is valid to assume that the flux linked with the rotor remains constant, this being brought about by an induced current in the rotor which balances the heavy demagnetising effect set up by the short-circuited armature. So $(\Phi + \Phi_L)$ remains constant, but owing to the increased m.m.f. involved, the flux leakage will increase considerably. With a constant total rotor flux, this can only increase at the expense of that flux crossing the air-gap. Consequently, this generates a reduced voltage, which, acting on the leakage reactance, gives the short circuit current.

It is more convenient for machine analysis to use the rated voltage E_0 and to invent a fictitious reactance that will give rise to the same current. This reactance is called the 'transient reactance' X'_d and is defined by the equation:

Transient current $\quad I'_d = \dfrac{E_o}{X'_d} \quad$ *...Equation A4.3*

It is greater than X_L, and the equivalent circuit is represented by Figure A4.8(b) where:

$$X'_d = \frac{X_{ad} X_f}{X_{ad} + X_f} + X_L$$

and X_f is the leakage reactance of the field winding

The above equation may also be written as:

$$X'_d = X_L + X'_f$$

where X'_f = effective leakage reactance of field winding

The flux will only be sustained at its relatively high value while the induced current flows in the field winding. As this current decays, so conditions will approach the steady state. Consequently, the duration of this phase will be determined by the time constant of the excitation winding. This is usually of the order of a second or less - hence the term 'transient' applied to characteristics associated with it.

A further point now arises. All synchronous machines have what is usually called a 'damper winding' or windings. In some cases, this may be a physical winding (like a field winding, but of fewer turns and located separately), or an 'effective' one (for instance, the solid iron rotor of a cylindrical rotor machine). Sometimes, both physical and effective damper windings may exist (as in some designs of cylindrical rotor generators, having both a solid iron rotor and a physical damper winding located in slots in the pole faces).

Under short circuit conditions, there is a transfer of flux from the main air-gap to leakage paths. This diversion is, to a small extent, opposed by the excitation winding and the main transfer will be experienced towards the pole tips.

The damper winding(s) is subjected to the full effect of flux transfer to leakage paths and will carry an induced current tending to oppose it. As long as this current can flow, the air-gap flux will be held at a value slightly higher than would be the case if only the excitation winding were present, but still less than the original open circuit flux Φ.

As before, it is convenient to use rated voltage and to create another fictitious reactance that is considered to be effective over this period. This is known as the 'sub-transient reactance' X''_d and is defined by the equation:

$$I''_d = \frac{E_o}{X''_d} \qquad \textit{...Equation A4.4}$$

where $\quad X''_d = X_L + \dfrac{X_{ad} X_f X_{kd}}{X_{ad} X_f + X_{kd} X_f + X_{ad} X_{kd}}$

or $\quad X''_d = X_L + X'_{kd}$

and X_{kd} = leakage reactance of damper winding(s)

X'_{kd} = effective leakage reactance of damper winding(s)

It is greater than X_L but less than X'_d and the corresponding equivalent circuit is shown in Figure A4.8(c).

Again, the duration of this phase depends upon the time constant of the damper winding. In practice this is approximately 0.05 seconds - very much less than the transient - hence the term 'sub-transient'.

Figure A4.9 shows the envelope of the symmetrical component of an armature short circuit current indicating the values described in the preceding analysis. The analysis of the stator current waveform resulting from a sudden short circuit test is traditionally the method by which these reactances are measured. However, the major limitation is that only direct axis parameters are measured. Detailed test methods for synchronous machines are given in references [Ref A4.2: IEC 60034-4] and [Ref A4.3: IEEE Standards 115/115A], and include other tests that are capable of providing more detailed parameter information.
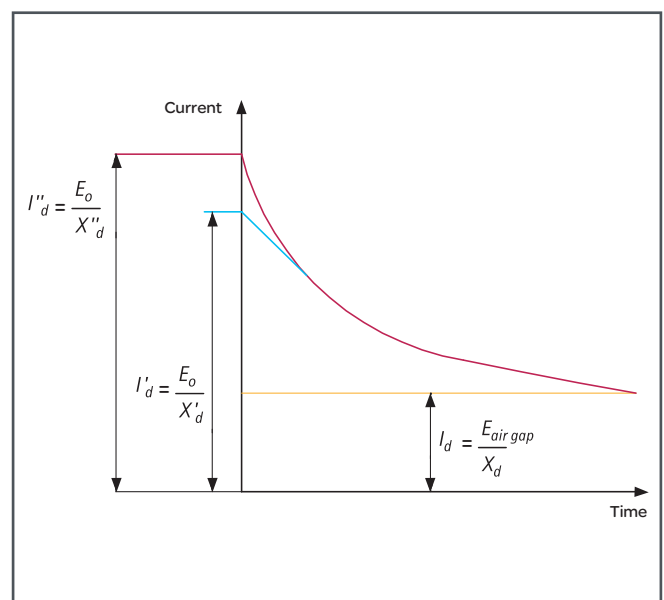

Figure A4.9:
Transient decay envelope of short-circuit current

A4

7. Asymmetry

The exact instant at which the short circuit is applied to the stator winding is of significance. If resistance is negligible compared with reactance, the current in a coil will lag the voltage by 90°, that is, at the instant when the voltage wave attains a maximum, any current flowing through would be passing through zero. If a short circuit were applied at this instant, the resulting current would rise smoothly and would be a simple a.c. component. However, at the moment when the induced voltage is zero, any current flowing must pass through a maximum (owing to the 90° lag). If a fault occurs at this moment, the resulting current will assume the corresponding relationship; it will be at its peak and in the ensuing 180° will go through zero to maximum in the reverse direction and so on. In fact the current must actually start from zero and so will follow a sine wave that is completely asymmetrical. Intermediate positions will give varying degrees of asymmetry.

This asymmetry can be considered to be due to a d.c. component of current which dies away because resistance is present.

The d.c. component of stator current sets up a d.c. field in the stator which causes a supply frequency ripple on the field current, and this alternating rotor flux has a further effect on the stator. This is best shown by considering the supply frequency flux as being represented by two half magnitude waves each rotating in opposite directions at supply frequency relative to the rotor. So, as viewed from the stator, one is stationary and the other rotating at twice supply frequency. The latter sets up second harmonic currents in the stator. Further development along these lines is possible but the resulting harmonics are usually negligible and normally neglected.

8. Machine reactances

Table A4.1 gives values of machine reactances for salient pole and cylindrical rotor machines typical of latest design practice. Also included are parameters for synchronous compensators – such machines are now rarely built, but significant numbers can still be found in operation.

Type of Machine	Salient pole synchronous condensers		Cylindrical rotor turbine generators			Salient pole generators	
	4 Pole	Multi-Pole	Air Cooled	Hydrogen Cooled	Hydrogen/ Water Cooled	4 Pole	Multi-Pole
Short circuit ratio	0.5-0.7	1.0-1.2	0.4-0.6	0.4-0.6	0.4-0.6	0.4-0.6	0.6-0.8
Direct axis synchronous reactance X_d (p.u.)	1.6-2.0	0.8-1.0	2.0-2.8	2.1-2.4	2.1-2.6	1.75-3.0	1.4-1.9
Quadrature axis synchronous reactance X_q (p.u.)	1.0-1.23	0.5-0.65	1.8-2.7	1.9-2.4	2.0-2.5	0.9-1.5	0.8-1.0
Direct axis transient reactance X'_d (p.u.)	0.3-0.5	0.2-0.35	0.2-0.3	0.27-0.33	0.3-0.36	0.26-0.35	0.24-0.4
Direct axis sub-transient reactance X''_d (p.u.)	0.2-0.4	0.12-0.25	0.15-0.23	0.19-0.23	0.21-0.27	0.19-0.25	0.16-0.25
Quadrature axis sub-transient reactance X''_q (p.u.)	0.25-0.6	0.15-0.25	0.16-0.25	0.19-0.23	0.21-0.28	0.19-0.35	0.18-0.24
Negative sequence reactance X_2 (p.u.)	0.25-0.5	0.14-0.35	0.16-0.23	0.19-0.24	0.21-0.27	0.16-0.27	0.16-0.23
Zero sequence reactance X_0 (p.u.)	0.12-0.16	0.06-0.10	0.06-0.1	0.1-0.15	0.1-0.15	0.01-0.1	0.045-0.23
Direct axis short circuit transient time constant T'_d (s)	1.5-2.5	1.0-2.0	0.6-1.3	0.7-1.0	0.75-1.0	0.4-1.1	0.25-1
Direct axis open circuit transient time constant T'_{do} (s)	5-10	3-7	6-12	6-10	6-9.5	3.0-9.0	1.7-4.0
Direct axis short circuit sub-transient time constant T''_d (s)	0.04-0.9	0.05-0.10	0.013-0.022	0.017-0.025	0.022-0.03	0.02-0.04	0.02-0.06
Direct axis open circuit sub-transient time constant T''_{do} (s)	0.07-0.11	0.08-0.25	0.018-0.03	0.023-0.032	0.025-0.035	0.035-0.06	0.03-0.1
Quadrature axis short circuit sub-transient time constant T''_q (s)	0.04-0.6	0.05-0.6	0.013-0.022	0.018-0.027	0.02-0.03	0.025-0.04	0.025-0.08
Quadrature axis open circuit sub-transient time constant T''_{qo} (s)	0.1-0.2	0.2-0.9	0.026-0.045	0.03-0.05	0.04-0.065	0.13-0.2	0.1-0.35

Table A4.1:
Typical synchronous generator parameters. Note: *all reactance values are unsaturated*

8. Machine reactances   A4

8.1 Synchronous reactance $X_d = X_L + X_{ad}$

The order of magnitude of X_L is normally 0.1-0.25 p.u., while that of X_{ad} is 1.0-2.5 p.u. The leakage reactance X_L can be reduced by increasing the machine size (derating), or increased by artificially increasing the slot leakage, but it will be noted that X_L is only about 10% of the total value of X_d and cannot exercise much influence.

The armature reaction reactance can be reduced by decreasing the armature reaction of the machine, which in design terms means reducing the ampere conductor or electrical (as distinct from magnetic) loading - this will often mean a physically larger machine. Alternatively the excitation needed to generate open-circuit voltage may be increased; this is simply achieved by increasing the machine air-gap, but is only possible if the excitation system is modified to meet the increased requirements.

In general, control of X_d is obtained almost entirely by varying X_{ad} , and in most cases a reduction in X_d will mean a larger and more costly machine. It is also worth noting that X_L normally changes in sympathy with X_{ad} , but is completely overshadowed by it.

The value $1/X_d$ has a special significance as it approximates to the short circuit ratio (S.C.R.), the only difference being that the S.C.R. takes saturation into account whereas X_d is derived from the air-gap line.

8.2 Transient reactance $X'_d = X_L + X'_f$

The transient reactance covers the behaviour of a machine in the period 0.1-3.0 seconds after a disturbance. This generally corresponds to the speed of changes in a system and therefore has a major influence in transient stability studies.

Generally, the leakage reactance X_L is equal to the effective field leakage reactance X'_f, about 0.1-0.25 p.u. The principal factor determining the value of X'f is the field leakage. This is largely beyond the control of the designer, in that other considerations are at present more significant than field leakage and hence take precedence in determining the field design.

X_L can be varied as already outlined, and, in practice, control of transient reactance is usually achieved by varying X_L.

8.3 Sub-transient reactance $X''_d = X_L + X'_{kd}$

The sub-transient reactance determines the initial current peaks following a disturbance and in the case of a sudden fault is of importance for selecting the breaking capacity of associated circuit breakers. The mechanical stresses on the machine reach maximum values that depend on this constant. The effective damper winding leakage reactance X'_{kd} is largely determined by the leakage of the damper windings and control of this is only possible to a limited extent. X'_{kd} normally has a value between 0.05 and 0.15 p.u. The major factor is X_L which, as indicated previously, is of the order of 0.1-0.25 p.u., and control of the sub-transient reactance is normally achieved by varying X_L.

It should be noted that good transient stability is obtained by keeping the value of X'_d low, which therefore also implies a low value of X''_d. The fault rating of switchgear, etc. will therefore be relatively high. It is not normally possible to improve transient stability performance in a generator without adverse effects on fault levels, and vice versa.

A4

9. Negative sequence reactance

Negative sequence currents can arise whenever there is any unbalance present in the system. Their effect is to set up a field rotating in the opposite direction to the main field generated by the rotor winding, so subjecting the rotor to double frequency flux pulsations. This gives rise to parasitic currents and heating; most machines are quite limited in the amount of such current which they are able to carry, both in the steady-state and transiently.

An accurate calculation of the negative sequence current capability of a generator involves consideration of the current paths in the rotor body. In a turbine generator rotor, for instance, they include the solid rotor body, slot wedges, excitation winding and end-winding retaining rings. There is a tendency for local over-heating to occur and, although possible for the stator, continuous local temperature measurement is not practical in the rotor. Calculation requires complex mathematical techniques to be applied, and involves specialist software.

In practice an empirical method is used, based on the fact that a given type of machine is capable of carrying, for short periods, an amount of heat determined by its thermal capacity, and for a long period, a rate of heat input which it can dissipate continuously. Synchronous machines are designed to be capable of operating continuously on an unbalanced system such that, with none of the phase currents exceeding the rated current, the ratio of the negative sequence current I_2 to the rated current I_N does not exceed the values given in Table A4.2. Under fault conditions, the machine shall also be capable of operation with the result of $(I_2 / I_N)^2$ and time in seconds (t) not exceeding the values given.

Rotor construction	Rotor cooling	Machine Type (S_N) / Rating (MVA)	Maximum I_2/I_N for continuous operation	Maximum $(I_2/I_N)^2$ t for continuous operation
Salient	Indirect	motors	0.1	20
		generators	0.08	20
		Synchronous condensers	0.1	20
	Direct	motors	0.08	15
		generators	0.05	15
		Synchronous condensers	0.08	15
Cylindrical	Indirectly cooled (air)	all	0.1	15
	Indirectly cooled (hydrogen)	all	0.1	10
	Directly cooled	<=350	0.08	8
		351-900	Note 1	Note 2
		901-1250	Note 1	5
		1251-1600	0.05	5

Note 1: Calculate as: $\dfrac{I_2}{I_N} = 0.08 - \dfrac{S_N - 350}{3 \times 10^4}$

Note 2: Calculate as: $\left(\dfrac{I_2}{I_N}\right)^2 t = 8 - 0.00545 (S_N - 350)$

Table A4.2:
Unbalanced operating conditions for synchronous machines (from IEC 60034-1)

10. Zero sequence reactance

If a machine is operating with an earthed neutral, a system earth fault will give rise to zero sequence currents in the machine. This reactance represents the machine's contribution to the total impedance offered to these currents. In practice it is generally low and often outweighed by other impedances present in the circuit.

11. Direct and quadrature axis values

The transient reactance is associated with the field winding and since on salient pole machines this is concentrated on the direct axis, there is no corresponding quadrature axis value. The value of reactance applicable in the quadrature axis is the synchronous reactance, that is, $X'_q = X_q$.

The damper winding (or its equivalent) is more widely spread and hence the sub-transient reactance associated with this has a definite quadrature axis value X''_q, which differs significantly in many generators from X''_d.

12. Effect on saturation on machine reactances

In general, any electrical machine is designed to avoid severe saturation of its magnetic circuit. However, it is not economically possible to operate at such low flux densities as to reduce saturation to negligible proportions, and in practice a moderate degree of saturation is accepted.

Since the armature reaction reactance X_{ad} is a ratio AT_{ar}/AT_e it is evident that AT_e will not vary in a linear manner for different voltages, while AT_{ar} will remain unchanged. The value of X_{ad} will vary with the degree of saturation present in the machine, and for extreme accuracy should be determined for the particular conditions involved in any calculation.

All the other reactances, namely X_L, X'_d and X''_d are true reactances and actually arise from flux leakage. Much of this leakage occurs in the iron parts of the machines and hence must be affected by saturation. For a given set of conditions, the leakage flux exists as a result of the net m.m.f. which causes it. If the iron circuit is unsaturated its reactance is low and leakage flux is easily established. If the circuits are highly saturated the reverse is true and the leakage flux is relatively lower, so the reactance under saturated conditions is lower than when unsaturated.

Most calculation methods assume infinite iron permeability and for this reason lead to somewhat idealised unsaturated reactance values. The recognition of a finite and varying permeability makes a solution extremely laborious and in practice a simple factor of approximately 0.9 is taken as representing the reduction in reactance arising from saturation.

It is necessary to distinguish which value of reactance is being measured when on test. The normal instantaneous short circuit test carried out from rated open circuit voltage gives a current that is usually several times full load value, so that saturation is present and the reactance measured will be the saturated value. This value is also known as the 'rated voltage' value since it is measured by a short circuit applied with the machine excited to rated voltage.

In some cases, if it is wished to avoid the severe mechanical strain to which a machine is subjected by such a direct short circuit, the test may be made from a suitably reduced voltage so that the initial current is approximately full load value. Saturation is very much reduced and the reactance values measured are virtually unsaturated values. They are also known as 'rated current' values, for obvious reasons.

13. Transformers

A transformer may be replaced in a power system by an equivalent circuit representing the self-impedance of, and the mutual coupling between, the windings. A two-winding transformer can be simply represented as a '**T**' network in which the cross member is the short-circuit impedance, and the column the excitation impedance. It is rarely necessary in fault studies to consider excitation impedance as this is usually many times the magnitude of the short-circuit impedance. With these simplifying assumptions a three-winding transformer becomes a star of three impedances and a four-winding transformer a mesh of six impedances.

The impedances of a transformer, in common with other plant, can be given in ohms and qualified by a base voltage, or in per unit or percentage terms and qualified by a base MVA. Care should be taken with multi-winding transformers to refer all impedances to a common base MVA or to state the base on which each is given. The impedances of static apparatus are independent of the phase sequence of the applied voltage; in consequence, transformer negative sequence and positive sequence impedances are identical. In determining the impedance to zero phase sequence currents, account must be taken of the winding connections, earthing, and, in some cases, the construction type. The existence of a path for zero

sequence currents implies a fault to earth and a flow of balancing currents in the windings of the transformer.

Practical three-phase transformers may have a phase shift between primary and secondary windings depending on the connections of the windings – delta or star. The phase shift that occurs is generally of no significance in fault level calculations as all phases are shifted equally. It is therefore ignored. It is normal to find delta-star transformers at the transmitting end of a transmission system and in distribution systems for the following reasons:

a. at the transmitting end, a higher step-up voltage ratio is possible than with other winding arrangements, while the insulation to ground of the star secondary winding does not increase by the same ratio

b. in distribution systems, the star winding allows a neutral connection to be made, which may be important in considering system earthing arrangements

c. the delta winding allows circulation of zero sequence currents within the delta, thus preventing transmission of these from the secondary (star) winding into the primary circuit. This simplifies protection considerations

A4

14. Transformer positive sequence equivalent circuits

The transformer is a relatively simple device. However, the equivalent circuits for fault calculations need not necessarily be quite so simple, especially where earth faults are concerned. The following two sections discuss the equivalent circuits of various types of transformers.

14.1 Two-winding transformers

The two-winding transformer has four terminals, but in most system problems, two-terminal or three-terminal equivalent circuits as shown in Figure A4.10 can represent it. In Figure A4.10(a), terminals A' and B' are assumed to be at the same potential. Hence if the per unit self-impedances of the windings are Z_{11} and Z_{22} respectively and the mutual impedance between them Z_{12}, the transformer may be represented by Figure A4.10(b). The circuit in Figure A4.10(b) is similar to that shown in Figure A2.14(a), and can therefore be replaced by an equivalent 'T' as shown in Figure A4.10(c) where:

$$\left.\begin{array}{l} Z_1 = Z_{11} - Z_{12} \\ Z_2 = Z_{22} - Z_{12} \\ Z_3 = Z_{12} \end{array}\right\} \qquad \text{...Equation A4.5}$$

Z_1 is described as the leakage impedance of winding AA' and Z_2 the leakage impedance of winding BB'.

Impedance Z_3 is the mutual impedance between the windings, usually represented by X_M, the magnetising reactance paralleled with the hysteresis and eddy current loops as shown in Figure A4.10(d).

If the secondary of the transformer is short-circuited, and Z_3 is assumed to be large with respect to Z_1 and Z_2, then the short-circuit impedance viewed from the terminals AA' is $Z_T = Z_1 + Z_2$ and the transformer can be replaced by a two-terminal equivalent circuit as shown in Figure A4.10(e).

The relative magnitudes of Z_T and X_M are of the order of 10% and 2000% respectively. Z_T and X_M rarely have to be considered together, so that the transformer may be represented either as a series impedance or as an excitation impedance, according to the problem being studied.

A typical power transformer is illustrated in Figure A4.11.

Figure A4.11:
Large transformer

14.2 Three-winding transformers

If excitation impedance is neglected the equivalent circuit of a three-winding transformer may be represented by a star of impedances, as shown in Figure A4.12, where P, T and S are the primary, tertiary and secondary windings respectively. The impedance of any of these branches can be determined by considering the short-circuit impedance between pairs of windings with the third open.

Figure A4.10:
Equivalent circuits for a two-winding transformer
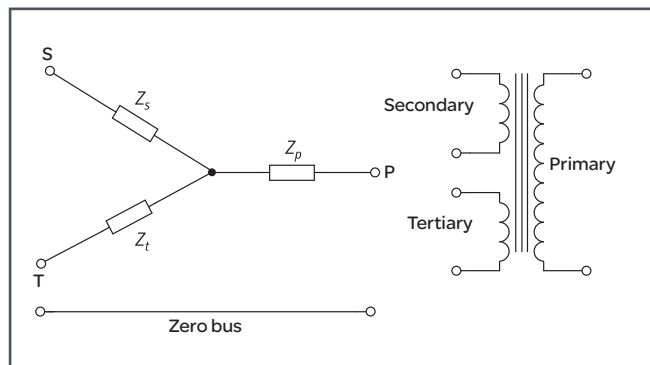
Figure A4.12:
Equivalent circuit for a three-winding transformer

15. Transformer zero sequence equivalent circuits

The flow of zero sequence currents in a transformer is only possible when the transformer forms part of a closed loop for uni-directional currents and ampere-turn balance is maintained between windings.

The positive sequence equivalent circuit is still maintained to represent the transformer, but now there are certain conditions attached to its connection into the external circuit. The order of excitation impedance is very much lower than for the positive sequence circuit; it will be roughly between 1 and 4 per unit, but still high enough to be neglected in most fault studies.

The mode of connection of a transformer to the external circuit is determined by taking account of each winding arrangement and its connection or otherwise to ground. If zero sequence currents can flow into and out of a winding, the winding terminal is connected to the external circuit (that is, link a is closed in Figure A4.13). If zero sequence currents can circulate in the winding without flowing in the external circuit, the winding terminal is connected directly to the zero bus (that is, link b is closed in Figure A4.13). Table A4.3 gives the zero sequence connections of some common two- and three-winding transformer arrangements applying the above rules.

The exceptions to the general rule of neglecting magnetising impedance occur when the transformer is star/star and either or both neutrals are earthed. In these circumstances the transformer is connected to the zero bus through the magnetising impedance. Where a three-phase transformer bank is arranged without interlinking magnetic flux (that is a three-phase shell type, or three single-phase units) and provided there is a path for zero sequence currents, the zero sequence impedance is equal to the positive sequence impedance. In the case of three-phase core type units, the zero sequence fluxes produced by zero sequence currents can find a high reluctance path, the effect being to reduce the zero sequence impedance to about 90% of the positive sequence impedance.

However, in hand calculations, it is usual to ignore this variation and consider the positive and zero sequence impedances to be equal. It is common when using software to perform fault calculations to enter a value of zero-sequence impedance in accordance with the above guidelines, if the manufacturer is unable to provide a value.
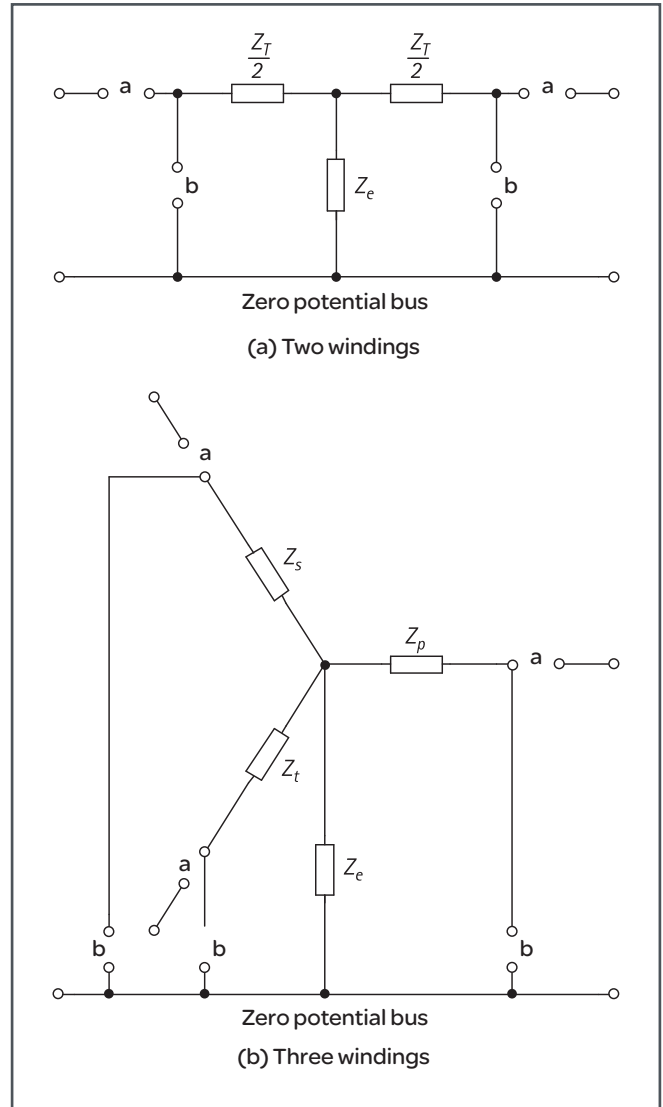
Figure A4.13:
Zero sequence equivalent circuits

15. Transformer zero sequence equivalent circuits

Connections and zero phase sequence currents	Zero phase sequence network

Table A4.3:
Zero sequence equivalent circuit connections
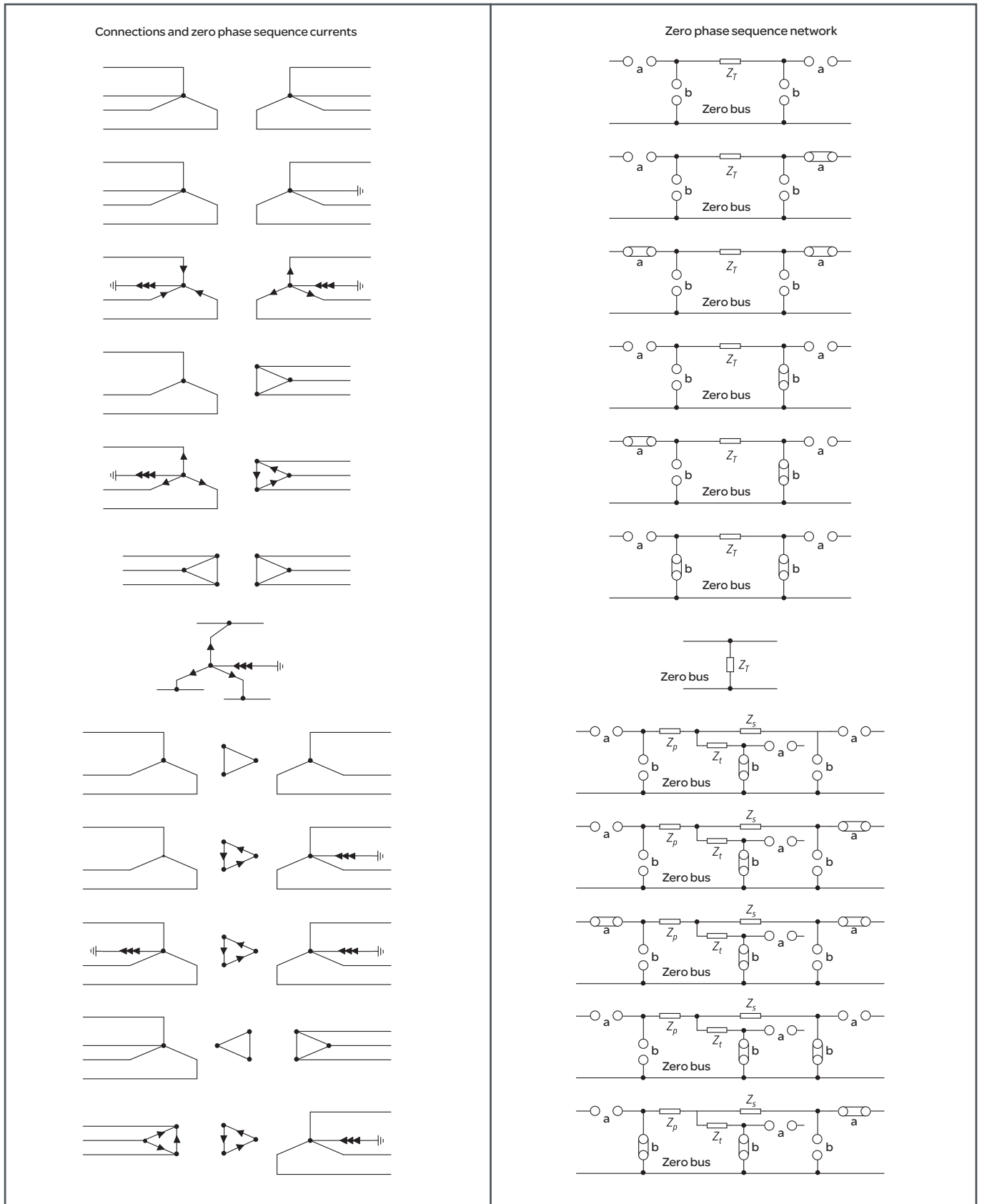
The auto-transformer is characterised by a single continuous winding, part of which is shared by both the high and low voltage circuits, as shown in Figure A4.14(a). The 'common' winding is the winding between the low voltage terminals whereas the remainder of the winding, belonging exclusively to the high voltage circuit, is designated the 'series' winding, and, combined with the 'common' winding, forms the 'series-common' winding between the high voltage terminals. The advantage of using an auto-transformer as opposed to a two-winding transformer is that the auto-transformer is smaller and lighter for a given rating. The disadvantage is that galvanic isolation between the two windings does not exist, giving rise to the possibility of large overvoltages on the lower voltage system in the event of major insulation breakdown.

Three-phase auto-transformer banks generally have star connected main windings, the neutral of which is normally connected solidly to earth. In addition, it is common practice to include a third winding connected in delta called the tertiary winding, as shown in Figure A4.14(b).

16.1 Positive sequence equivalent circuit

The positive sequence equivalent circuit of a three-phase auto- transformer bank is the same as that of a two- or three-winding transformer. The star equivalent for a three-winding transformer, for example, is obtained in the same manner, with the difference that the impedances between windings are designated as follows:

$$Z_L = \frac{1}{2}\left(Z_{sc-c} + Z_{c-t} - Z_{sc-t}\right)$$
$$Z_H = \frac{1}{2}\left(Z_{sc-c} + Z_{sc-t} - Z_{c-t}\right)$$
$$Z_T = \frac{1}{2}\left(Z_{sc-t} + Z_{c-t} - Z_{sc-c}\right)$$

...Equation A4.8

where:

Z_{sc-t} = impedance between 'series common' and tertiary windings

Z_{sc-c} = impedance between 'series common' and 'common' windings

Z_{sc-t} = impedance between 'common' and tertiary windings

When no load is connected to the delta tertiary, the point T will be open-circuited and the short-circuit impedance of the transformer becomes $Z_L + Z_H = Z_{sc-c}$, that is, similar to the equivalent circuit of a two-winding transformer, with magnetising impedance neglected; see Figure A4.14(c).

16.2 Zero sequence equivalent circuit

The zero sequence equivalent circuit is derived in a similar manner to the positive sequence circuit, except that, as there is no identity for the neutral point, the current in the neutral

(a) Circuit diagram

(b) Circuit diagram with tertiary winding

(c) Positive sequence impedance

(d) Zero sequence equivalent circuit

(e) Equivalent circuit with isolated neutral
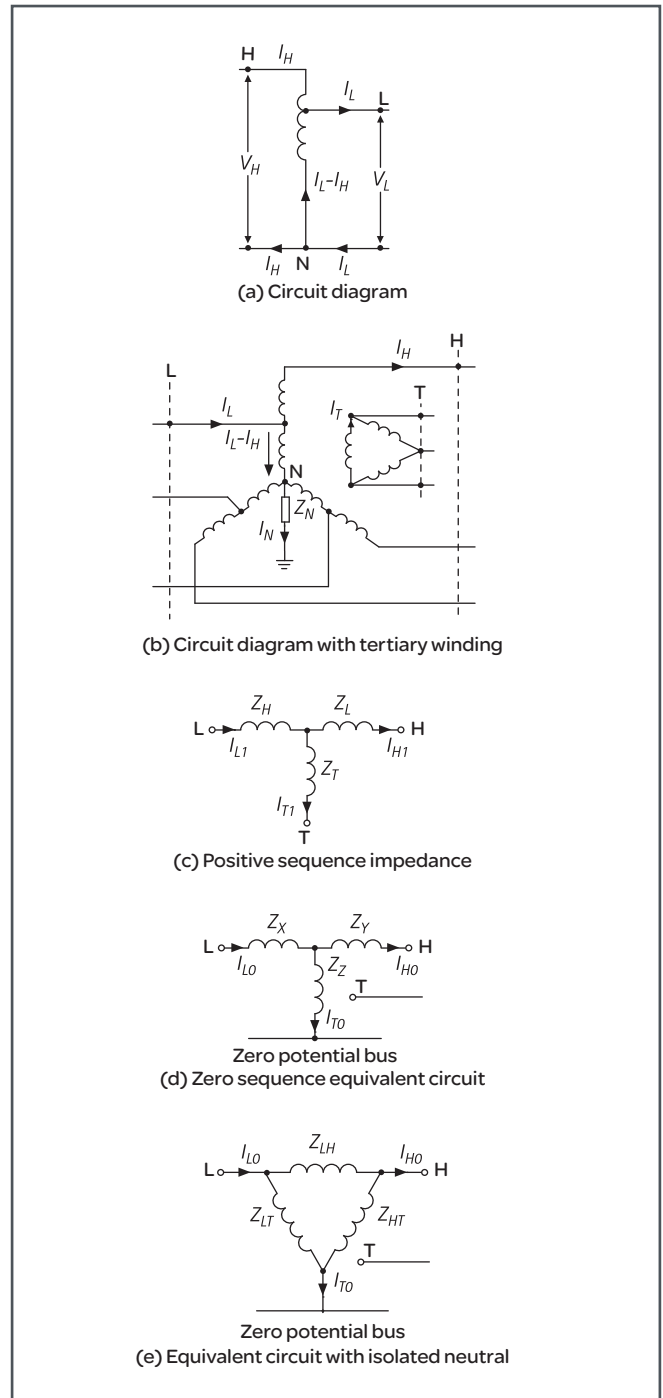
Figure A4.14:
Equivalent circuit of auto-transformer

and the neutral voltage cannot be given directly. Furthermore, in deriving the branch impedances, account must be taken of an impedance in the neutral Z_n, as shown in the following equations, where Z_x, Z_y and Z_z are the impedances of the low, high and tertiary windings respectively and N is the ratio between the series and common windings.

16. Auto-transformers

$$Z_x = Z_L + 3Z_n \frac{N}{(N+1)}$$

$$Z_y = Z_H - 3Z_n \frac{N}{(N+1)^2}$$

$$Z_z = Z_T + 3Z_n \frac{1}{(N+1)}$$

$$...Equation\ A4.9$$

Figure A4.14(d) shows the equivalent circuit of the transformer bank. Currents I_{L0} and I_{H0} are those circulating in the low and high voltage circuits respectively. The difference between these currents, expressed in amperes, is the current in the common winding.

The current in the neutral impedance is three times the current in the common winding.

16.3 Special conditions of neutral earthing

With a solidly grounded neutral, $Z_n = 0$, the branch impedances Z_x, Z_y, Z_z, become Z_L, Z_H, Z_T, that is, identical to the corresponding positive sequence equivalent circuit, except that the equivalent impedance Z_T of the delta tertiary is connected to the zero potential bus in the zero sequence network.

When the neutral is ungrounded $Z_n = \mu$ and the impedances of the equivalent star also become infinite because there are apparently no paths for zero sequence currents between the windings, although a physical circuit exists and ampere-turn balance can be obtained. A solution is to use an equivalent delta circuit (see Figure A4.14(e)), and evaluate the elements of the delta directly from the actual circuit. The method requires three equations corresponding to three assumed operating conditions. Solving these equations will relate the delta impedances to the impedance between the series and tertiary windings, as follows:

$$Z_x = Z_L + 3Z_n \frac{N}{(N+1)}$$

$$Z_y = Z_H - 3Z_n \frac{N}{(N+1)^2}$$

$$Z_z = Z_T + 3Z_n \frac{1}{(N+1)}$$

$$...Equation\ A4.10$$

With the equivalent delta replacing the star impedances in the auto-transformer zero sequence equivalent circuit the transformer can be combined with the system impedances in the usual manner to obtain the system zero sequence diagram.

17. Transformer impedances

In the vast majority of fault calculations, the Protection Engineer is only concerned with the transformer leakage impedance; the magnetising impedance is neglected, as it is very much higher. Impedances for transformers rated 200MVA or less are given in IEC 60076 and repeated in Table A4.4, together with an indication of X/R values (not part of IEC 60076). These impedances are commonly used for transformers installed in industrial plants. Some variation is possible to assist in controlling fault levels or motor starting, and typically up to ±10% variation on the impedance values given in the table is possible without incurring a significant cost penalty. For these transformers, the tapping range is small, and the variation of impedance with tap position is normally neglected in fault level calculations.

For transformers used in electricity distribution networks, the situation is more complex, due to an increasing trend to assign importance to the standing (or no-load) losses represented by the magnetising impedance. This can be adjusted at the design stage but there is often an impact on the leakage reactance in consequence. In addition, it may be more important to control fault levels on the LV side than to improve motor starting voltage drops. Therefore, departures from the IEC 60076 values are commonplace.

MVA	Z% HV/LV	X/R	Tolerance on Z%
<0.630	4.00	1.5	+/- 10.0
0.631-1.25	5.00	3.5	+/- 10.0
1.251 - 3.15	6.25	6.0	+/- 10.0
3.151 - 6.3	7.15	8.5	+/- 10.0
6.301-12.5	8.35	13.0	+/- 10.0
12.501- 25.0	10.00	20.0	+/- 7.5
25.001 - 200	12.50	45.0	+/- 7.5
>200	by agreement		

Table A4.4:
Transformer impedances - IEC 60076

IEC 60076 does not make recommendations of nominal impedance in respect of transformers rated over 200MVA, while generator transformers and a.c. traction supply transformers have impedances that are usually specified as a result of Power Systems Studies to ensure satisfactory performance. Typical values of transformer impedances covering a variety of transformer designs are given in Tables A4.5 – A4.8. Where appropriate, they include an indication of the impedance variation at the extremes of the taps given. Transformers designed to work at 60Hz will have substantially the same impedance as their 50Hz counterparts.

17. Transformer impedances   A4

MVA	Primary kV	Primary Taps	Secondary kV	Z% HV/LV	X/R ratio
7.5	33	+5.72% -17.16%	11	7.5	15
7.5	33	+5.72% -17.16%	11	7.5	17
8	33	+5.72% -17.16%	11	8	9
11.5	33	+5.72% -17.16%	6.6	11.5	24
11.5	33	+5.72% -17.16%	6.6	11.5	24
11.5	33	+5.72% -17.16%	11	11.5	24
11.5	33	+5.72% -17.16%	11	11.5	26
11.5	33	+4.5% -18%	6.6	11.5	24
12	33	+5% -15%	11.5	12	27
12	33	±10%	11.5	12	27
12	33	±10%	11.5	12	25
15	66	+9% -15%	11.5	15	14
15	66	+9% -15%	11.5	15	16
16	33	±10%	11.5	16	16
16	33	+5.72% -17.16%	11	16	30
16	33	+5.72% -17.16%	6.6	16	31
19	33	+5.72% -17.16%	11	19	37
30	33	+5.72% -17.16%	11	30	40
24	33	±10%	6.9	24	25
30	33	±10%	6.9	24	25
30	132	+10% -20%	11	21.3	43
30	132	+10% -20%	11	25	30
30	132	+10% -20%	11	23.5	46
40	132	+10% -20%	11	27.9	37
45	132	+10% -20%	33	11.8	18
60	132	+10% -20%	33	16.7	28
60	132	+10% -20%	33	17.7	26
60	132	+10% -20%	33	14.5	25
60	132	+10% -20%	66	11	25
60	132	+10% -20%	11/11	35.5	52
60	132	+9.3% -24%	11/11	36	75
60	132	+9.3% -24%	11/11	35.9	78
65	140	+7.5% -15%	11	12.3	28
90	132	+10% -20%	33	24.4	60
90	132	+10% -20%	66	15.1	41

Table A4.5:
Impedances of two winding distribution transformers – Primary voltage <200kV

MVA	Primary kV	Primary Taps	Secondary kV	Tertiary kV	Z% HV/LV	X/R ratio
20	220	+12.5% -7.5%	6.9	-	9.9	18
20	230	+12.5% -7.5%	6.9	-	10-14	13
57	275	±10%	11.8	7.2	18.2	34
74	345	+14.4% -10%	96	12	8.9	25
79.2	220	+10% -15%	11.6	11	18.9	35
120	275	+10% -15%	34.5	-	22.5	63
125	230	±16.8%	66	-	13.1	52
125	230	not known	150	-	10-14	22
180	275	±15%	66	13	22.2	38
255	230	+10%	16.5	-	14.8	43

Table A4.6: Impedances of two winding distribution transformers – Primary voltage >200kV

(a) Three-phase units

MVA	Primary kV	Primary Taps	Secondary kV	Z% HV/LV	X/R ratio
95	132	±10%	11	13.5	46
140	157.5	±10%	11.5	12.7	41
141	400	±5%	15	14.7	57
151	236	±5%	15	13.6	47
167	145	+7.5% -16.5%	15	25.7	71
180	289	±5%	16	13.4	34
180	132	±10%	15	13.8	40
247	432	+3.75% -16.25%	15.5	15.2	61
250	300	+11.2% -17.6%	15	28.6	70
290	420	±10%	15	15.7	43
307	432	+3.75% -16.25%	15.5	15.3	67
346	435	+5% -15%	17.5	16.4	81
420	432	+5.55% -14.45%	22	16	87
437.8	144.1	+10.8% -21.6%	21	14.6	50
450	132	±10%	19	14	49
600	420	±11.25%	21	16.2	74
716	525	±10%	19	15.7	61
721	362	+6.25% -13.75%	22	15.2	83
736	245	+7% -13%	22	15.5	73
900	525	+7% -13%	23	15.7	67

(b) Single-phase units

MVA / phase	Primary kV	Primary Taps	Secondary kV	Z% HV/LV	X/R ratio
266.7	$432/\sqrt{3}$	+6.67% -13.33%	23.5	15.8	92
266.7	$432/\sqrt{3}$	+6.6% -13.4%	23.5	15.7	79
277	$515/\sqrt{3}$	±5%	22	16.9	105
375	$525/\sqrt{3}$	+6.66% -13.32%	26	15	118
375	$420/\sqrt{3}$	+6.66% -13.32%	26	15.1	112

Table A4.7:
Impedances of generator transformers

MVA	Primary kV	Primary Taps	Secondary kV	Secondary Taps	Tertiary kV	Z% HV/LV	X/R ratio
100	66	-	33	-	-	10.7	28
180	275	-	132	±15%	13	15.5	55
240	400	-	132	+15% -5%	13	20.2	83
240	400	-	132	+15% -5%	13	20.0	51
240	400	-	132	+15% -5%	13	20.0	61
250	400	-	132	+15% -5%	13	10-13	50
500	400	-	132	+0% -15%	22	14.3	51
750	400	-	275	-	13	12.1	90
1000	400	-	275	-	13	15.8	89
1000	400	-	275	-	33	17.0	91
333.3	$500/\sqrt{3}$	±10%	$230/\sqrt{3}$		22	18.2	101

Table A4.8:
Auto-transformer data

A4

18. Overhead lines and cables

In this section a description of common overhead lines and cable systems is given, together with tables of their important characteristics. The formulae for calculating the characteristics are developed to give a basic idea of the factors involved, and to enable calculations to be made for systems other than those tabulated.

A transmission circuit may be represented by an equivalent π or T network using lumped constants as shown in Figure A4.15. Z is the total series impedance $(R + jX)\,L$ and Y is the total shunt admittance $(G + jB)\,L$, where L is the circuit length. The terms inside the brackets in Figure A4.15 are correction factors that allow for the fact that in the actual circuit the parameters are distributed over the whole length of the circuit and not lumped, as in the equivalent circuits.

With short lines it is usually possible to ignore the shunt admittance, which greatly simplifies calculations, but on longer lines it must be included. Another simplification that can be made is that of assuming the conductor configuration to be symmetrical. The self-impedance of each conductor becomes Z_p, and the mutual impedance between conductors becomes Z_m. However, for rigorous calculations a detailed treatment is necessary, with account being taken of the spacing of a conductor in relation to its neighbour and earth.

(a) Actual transmission circuit

(b) π Equivalent

(c) T Equivalent

Note: Z and Y in (b) and (c) are the total series impedance and shunt admittance respectively.
$Z=(R+jX)L$ and $Y=(G+jB)L$ where L is the circuit length.

$$\frac{sinh \sqrt{ZY}}{\sqrt{ZY}} = 1 + \frac{ZY}{6} + \frac{Z^2 Y^2}{120} + \frac{Z^3 Y^3}{5040} + ...$$

$$\frac{tanh \sqrt{ZY}}{\sqrt{ZY}} = 1 - \frac{ZY}{12} + \frac{Z^2 Y^2}{120} + \frac{17 Z^3 Y^3}{20160} + ...$$
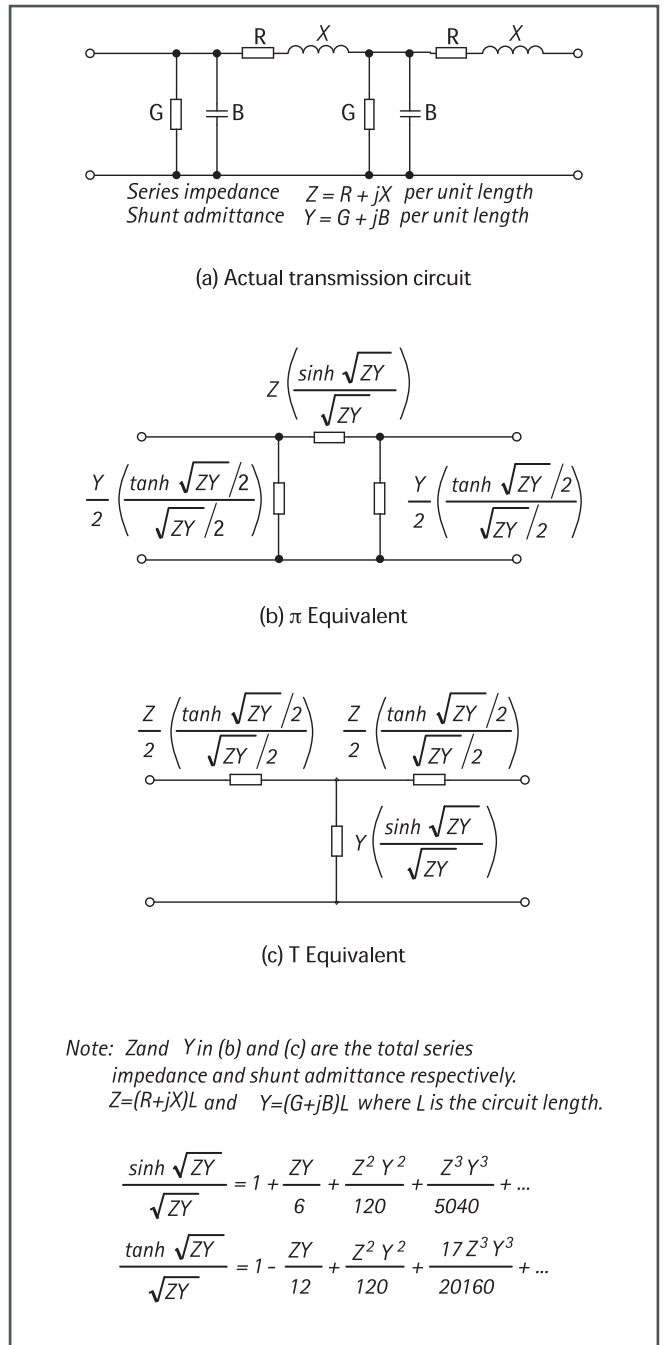
Figure A4.15:
Transmission circuit equivalents

19. Calculation of series impedance A4

The self impedance of a conductor with an earth return and the mutual impedance between two parallel conductors with a common earth return are given by the Carson equations:

$$Z_p = R + 0.000988\,f + j0.0029\,f\log_{10}\frac{D_e}{dc}$$

$$Z_p = 0.000988\,f + j0.0029\,f\log_{10}\frac{D_e}{D}$$

...Equation A4.11

where:

R = conductor a.c. resistance (ohms/km)

dc = geometric mean radius of a single conductor

D = spacing between the parallel conductors

f = system frequency

D_e = equivalent spacing of the earth return path

= $216\sqrt{p/f}$ where p is earth resistivity (ohms/cm³)

The above formulae give the impedances in ohms/km. It should be noted that the last terms in Equation A4.11 are very similar to the classical inductance formulae for long straight conductors.

The geometric means radius (GMR) of a conductor is an equivalent radius that allows the inductance formula to be reduced to a single term. It arises because the inductance of a solid conductor is a function of the internal flux linkages in addition to those external to it. If the original conductor can be replaced by an equivalent that is a hollow cylinder with infinitesimally thin walls, the current is confined to the surface of the conductor, and there can be no internal flux. The geometric mean radius is the radius of the equivalent conductor. If the original conductor is a solid cylinder having a radius r its equivalent has a radius of $0.779\,r$.

It can be shown that the sequence impedances for a symmetrical three-phase circuit are:

$$Z_1 = Z_2 = Z_p - Z_m$$

$$Z_0 = Z_p + 2Z_m$$

...Equation A4.12

where Z_p and Z_m are given by Equation A4.11.

Substituting Equation A4.11 in Equation A4.12 gives:

$$Z_1 = Z_2 = R + j0.0029f\log_{10}\frac{D}{dc}$$

$$Z_0 = R + 0.00296f + j0.00869f\log_{10}\frac{D_e}{\sqrt[3]{dcD^2}}$$

...Equation A4.13

In the formula for Z_0 the expression $\sqrt[3]{dcD^2}$ is the geometric mean radius of the conductor group.

Where the circuit is not symmetrical, the usual case, symmetry can be maintained by transposing the conductors so that each conductor is in each phase position for one third of the circuit length. If A, B and C are the spacings between conductors bc, ca and ab then D in the above equations becomes the geometric mean distance between conductors, equal to $\sqrt[3]{ABC}$.

Writing $D_c = \sqrt[3]{dcD^2}$, the sequence impedances in ohms/km at 50Hz become:

$$Z_1 = Z_2 = R + j0.145\log_{10}\frac{\sqrt[3]{ABC}}{dc}$$

$$Z_0 = (R + 0.148) + j0.434\log_{10}\frac{D_e}{D_c}$$

...Equation A4.14

20. Calculation of shunt impedance

It can be shown that the potential of a conductor a above ground due to its own charge qa and a charge $-qa$ on its image is:

$$V_a = 2\ qa\ log_e \frac{2h}{r} \qquad ...Equation\ A4.15$$

where h is the height above ground of the conductor and r is the radius of the conductor, as shown in Figure A4.16.
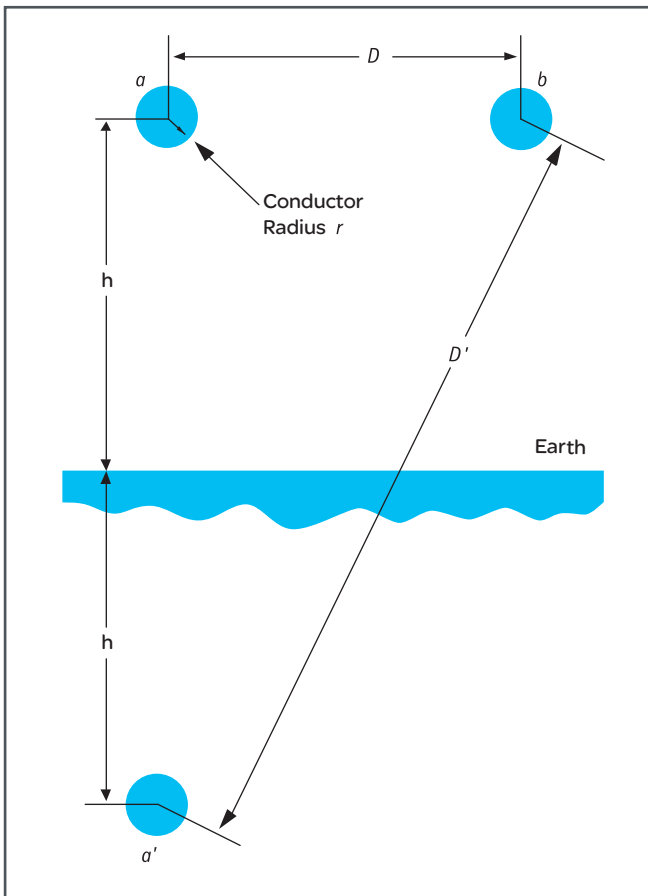
Figure A4.16:
Geometry of two parallel conductors a and b the image of a (a')

Similarly, it can be shown that the potential of a conductor a due to a charge qb on a neighbouring conductor b and the charge $-qb$ on its image is:

$$V_a' = 2\ qb\ log_e \frac{D'}{D} \qquad ...Equation\ A4.16$$

where D is the spacing between conductors a and b and D' is the spacing between conductor b and the image of conductor a as shown in Figure A4.14.

Since the capacitance $C = q/V$ and the capacitive reactance $Xc = 1/\omega C$, it follows that the self and mutual capacitive reactance of the conductor system in Figure A4.16 can be

obtained directly from Equations A4.15 and A4.16. Further, as leakage can usually be neglected, the self and mutual shunt impedances Z'_p and Z'_m in megohm-km at a system frequency of 50Hz are:

$$\left. \begin{array}{l} Z'_p = -j0.132\ log_{10} \dfrac{2h}{r} \\[2em] Z'_m = -j0.132\ log_{10} \dfrac{D'}{D} \end{array} \right\} \qquad ...Equation\ A4.17$$

Where the distances above ground are great in relation to the conductor spacing, which is the case with overhead lines, $2h=D'$. From Equation A4.12, the sequence impedances of a symmetrical three-phase circuit are:

$$\left. \begin{array}{l} Z_1 = Z_2 = -j0.132\ log_{10} \dfrac{D}{r} \\[2em] Z_0 = -j0.396\ log_{10} \dfrac{D'}{\sqrt[3]{rD^2}} \end{array} \right\} \qquad ...Equation\ A4.18$$

It should be noted that the logarithmic terms above are similar to those in Equation A4.13 except that r is the actual radius of the conductors and D' is the spacing between conductors and their images.

Again, where the conductors are not symmetrically spaced but transposed, Equation A4.18 can be re-written making use of the geometric mean distance between conductors, $\sqrt[3]{ABC}$, and giving the distance of each conductor above ground, that is, h_a, h_b, h_c, as follows:

$$\left. \begin{array}{l} Z_1 = Z_2 = -j0.132\ log_{10} \dfrac{\sqrt[3]{ABC}}{r} \\[2em] Z_0 = -j0.132\ log_{10} \dfrac{8h_a\ h_b\ h_c}{r\sqrt[3]{A^2B^2C^2}} \end{array} \right\} \qquad ...Equation\ A4.19$$

20. Calculation of shunt impedance

Single circuit

U_n (kV)	a (m)
3.3	0.55
6.6	0.67
11	0.8
22	1
33	1.25

A B C
a a

Single circuit
U_n= 63kV/66kV/90kV

3.80
0.50
6.0
R2
R1
W
X
Y

Single circuit
U_n= 90kV

A   A
A=3.5m

Single circuit
U_n= 63kV/90kV

6.6
2
2
2.50
a
2.50
2.70
R1
W
Y

U_n(kV)	a(m)
63	1.4
90	1.85

Double circuit
U_n= 63kV/90kV

1.75 - K
2.00 - N
c
3.30 a
3.30 b
d   a
R1
W
Y

	a	b	c	d
63 kV (K)	3.0	3.7	3.0	1.4
90 kV (N)	3.1	3.8	3.8	1.85

Double circuit
U_n= 63kV/66kV/90kV

4.00
3.50   2.8 2.8
3.50   3.5 3.5   a
3.0 3.0

U_n (kV)	a (m)
63	1.40
66	1.40
90	1.85

Single circuit
U_n= 110kV

6.60
2
2
2.75
a
2.75
3.10
R1
W
Y

Double circuit
U_n= 138kV

3.4   a
4.1   b
3.7   a
R1
W
Y

a=3.7m
b=4.6m

Double circuit
U_n= 170kV

6.20
3.9 3.9
5.80
4.2   4.2
8.0   8.0

Figure A4.17:
Typical OHL configurations (not to scale)

A4

20. Calculation of shunt impedance

Single circuit
U_n = 245kV

Double circuit
U_n = 245kV

	a	b	c	d
A	3.5	3.8	4.1	2.8
B	4.2	4.5	4.8	2.8
C	4.2	4.5	4.8	2.8

Double circuit
U_n = 245kV

n	n1	n2	p
9.5	5.0	4.5	6.3
9.8	5.0	4.8	6.3

Single circuit
U_n = 245kV

Double circuit
U_n = 420kV

Double circuit
U_n = 420kV

Single circuit
U_n = 550kV

Double circuit
U_n = 550kV

Single circuit
U_n = 800kV
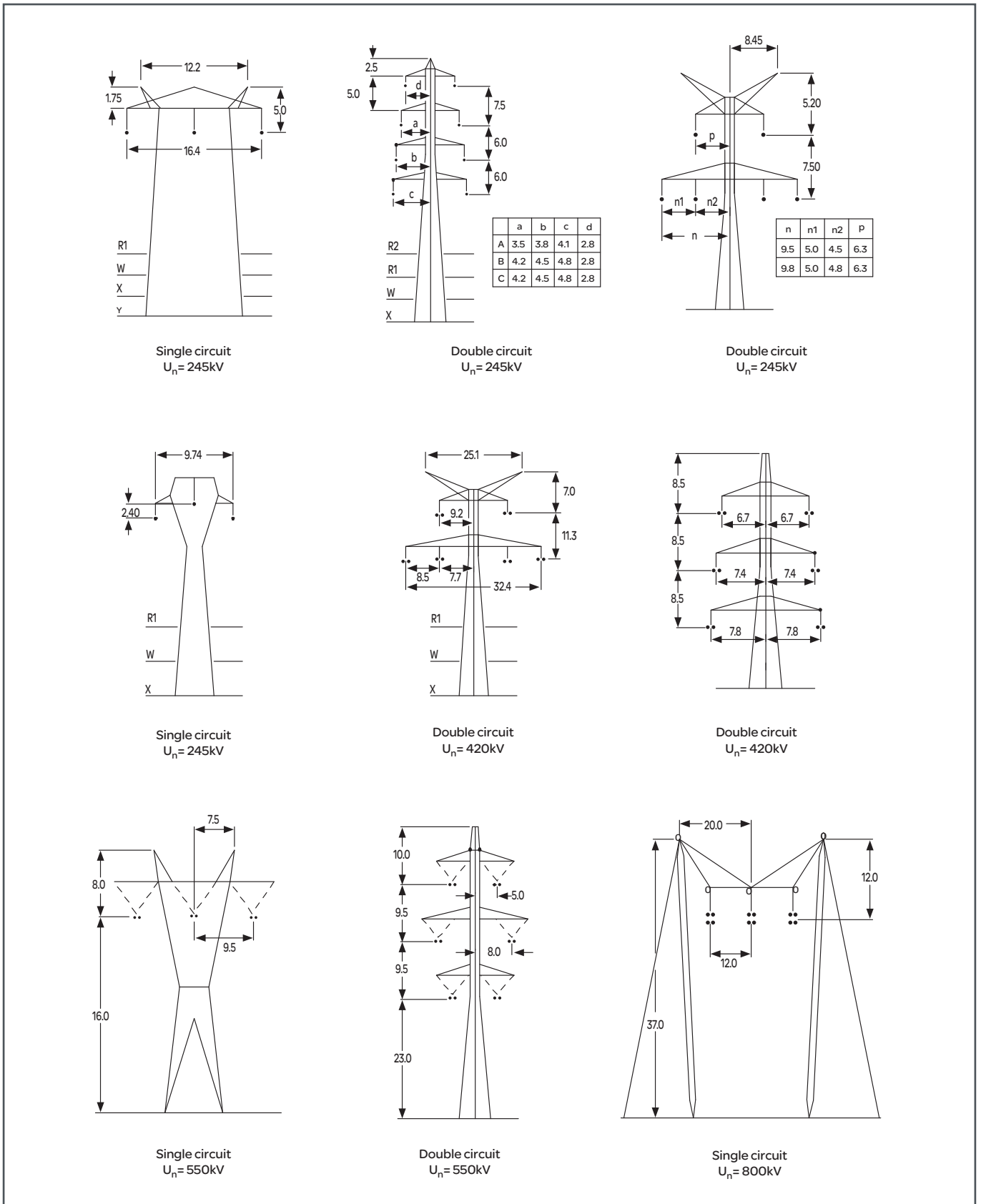
Figure A4.17 (cont.):
Typical OHL configurations (not to scale)

21. Overhead line circuits with or without earth wires

Typical configurations of overhead line circuits are given in Figure A4.17. Tower heights are not given as they vary considerably according to the design span and nature of the ground. As indicated in some of the tower outlines, some tower designs are designed with a number of base extensions for this purpose. Figure A4.18 shows a typical tower.

Figure A4.18:
Typical overhead line tower

In some cases, the phase conductors are not symmetrically disposed to each other and therefore, as previously indicated, electrostatic and electromagnetic unbalance will result, which can be largely eliminated by transposition. Modern practice is to build overhead lines without transposition towers to reduce costs; this must be taken into account in rigorous calculations of the unbalances. In other cases, lines are formed of bundled conductors, that is conductors formed of two, three or four separate conductors. This arrangement minimises losses when voltages of 220kV and above are involved.

It should be noted that the line configuration and conductor spacings are influenced, not only by voltage, but also by many other factors including type of insulators, type of support, span length, conductor sag and the nature of terrain and external climatic loadings. Therefore, there can be large variations in spacings between different line designs for the same voltage level, so those depicted in Figure A4.17 are only typical examples.

When calculating the phase self and mutual impedances, Equations A4.11 and A4.17 may be used, but it should be remembered that in this case Z_p is calculated for each conductor and Z_m for each pair of conductors. This section is not, therefore, intended to give a detailed analysis, but rather to show the general method of formulating the equations, taking the calculation of series impedance as an example and assuming a single circuit line with a single earth wire.

The phase voltage drops V_a, V_b, V_c of a single circuit line with a single earth wire due to currents I_a, I_b, I_c flowing in the phases and I_e in the earth wire are:

$$
\left.
\begin{aligned}
V_a &= Z_{aa}I_a + Z_{ab}I_b + Z_{ac}I_c + Z_{ae}I_e \\
V_b &= Z_{ba}I_a + Z_{bb}I_b + Z_{bc}I_c + Z_{be}I_e \\
V_c &= Z_{ca}I_a + Z_{cb}I_b + Z_{cc}I_c + Z_{ce}I_e \\
0 &= Z_{ea}I_a + Z_{eb}I_b + Z_{ec}I_c + Z_{ee}I_e
\end{aligned}
\right\} \quad \text{...Equation A4.20}
$$

where:

$$
Z_{aa} = R + 0.000988\,f + j0.0029\,f\,log_{10}\frac{D_e}{dc}
$$

$$
Z_{ab} = 0.000988\,f + j0.0029\,f\,log_{10}\frac{D_e}{D}
$$

and so on.

The equation required for the calculation of shunt voltage drops is identical to Equation A4.20 in form, except that primes must be included, the impedances being derived from Equation A4.17.

From Equation A4.20 it can be seen that:

$$
-I_e = \frac{Z_{ea}}{Z_{ee}}I_a + \frac{Z_{eb}}{Z_{ee}}I_b + \frac{Z_{ec}}{Z_{ee}}I_c
$$

Making use of this relation, the self and mutual impedances of the phase conductors can be modified using the following formula:

$$
J_{nm} = Z_{nm} - \frac{Z_{ne}Z_{me}}{Z_{ee}} \quad \text{...Equation A4.21}
$$

For example:

$$
J_{aa} = Z_{aa} - \frac{Z_{ae}^2}{Z_{ee}}
$$

$$
J_{ab} = Z_{ab} - \frac{Z_{ae}Z_{be}}{Z_{ee}} \quad \text{and so on.}
$$

So Equation A4.20 can be simplified while still taking account of the effect of the earth wire by deleting the fourth row and fourth column and substituting J_{aa} for Z_{aa}, J_{ab} for Z_{ab}, and so on, calculated using Equation A4.21. The single circuit line

A4

21. Overhead line circuits with or without earth wires

with a single earth wire can therefore be replaced by an equivalent single circuit line having phase self and mutual impedances J_{aa} , J_{ab} and so on.

It can be shown from the symmetrical component theory given in Chapter [A3: Fault Calculations] that the sequence voltage drops of a general three-phase circuit are:

$$
\left.\begin{array}{l}
V_0 = Z_{00}\,I_0 + Z_{01}\,I_1 + Z_{02}\,I_2 \\[4pt]
V_1 = Z_{10}\,I_0 + Z_{11}\,I_1 + Z_{12}\,I_2 \\[4pt]
V_2 = Z_{20}\,I_0 + Z_{21}\,I_1 + Z_{22}\,I_2
\end{array}\right\}
$$

...Equation A4.22

And, from Equation A4.20 modified as indicated above and Equation A4.22, the sequence impedances are:

The development of these equations for double circuit lines with two earth wires is similar except that more terms are involved.

The sequence mutual impedances are very small and can usually be neglected; this also applies for double circuit lines except for the mutual impedance between the zero sequence circuits, namely $(Z_{00'} = Z_{0'0})$. Table A4.9 gives typical values of all sequence self and mutual impedances some single and double circuit lines with earth wires. All conductors are 400mm^2 ACSR, except for the 132kV double circuit example where they are 200mm^2.

$$
\left.\begin{array}{l}
Z_{00} = \dfrac{1}{3}\left(J_{aa}+J_{bb}+J_{cc}\right)+\dfrac{2}{3}\left(J_{ab}+J_{bc}+J_{ac}\right) \\[14pt]
Z_{11} = \dfrac{1}{3}\left(J_{aa}+J_{bb}+J_{cc}\right)-\dfrac{1}{3}\left(J_{ab}+J_{bc}+J_{ac}\right) \\[14pt]
Z_{12} = \dfrac{1}{3}\left(J_{aa}+a^2 J_{bb}+a J_{cc}\right)+\dfrac{2}{3}\left(a J_{ab}+a^2 J_{ac}+J_{bc}\right) \\[14pt]
Z_{21} = \dfrac{1}{3}\left(J_{aa}+a J_{bb}+a^2 J_{cc}\right)+\dfrac{2}{3}\left(a^2 J_{ab}+a J_{ac}+J_{bc}\right) \\[14pt]
Z_{20} = \dfrac{1}{3}\left(J_{aa}+a^2 J_{bb}+a J_{cc}\right)-\dfrac{1}{3}\left(a J_{ab}+a^2 J_{ac}+J_{bc}\right) \\[14pt]
Z_{10} = \dfrac{1}{3}\left(J_{aa}+a J_{bb}+a^2 J_{cc}\right)-\dfrac{1}{3}\left(a^2 J_{ab}+a J_{ac}+J_{bc}\right) \\[14pt]
Z_{22} = Z_{11} \\[8pt]
Z_{01} = Z_{20} \\[8pt]
Z_{02} = Z_{10}
\end{array}\right\}
$$

...Equation A4.23

Sequence impedance	132kV Single circuit line (400 mm²)	380kV Single circuit line (400 mm²)	132kV Double circuit line (200 mm²)	275kV Double circuit line (400 mm²)
$Z_{00} = (Z_{0'0'})$	1.0782 < 73°54'	0.8227 < 70°36'	1.1838 < 71°6'	0.9520 < 76°46'
$Z_{11} = Z_{22} = (Z_{1'1'})$	0.3947 < 78°54'	0.3712 < 75°57'	< 66°19'	0.3354 < 74°35'
$(Z_{0'0} = Z_{00'})$			0.6334 < 71°2'	0.5219 < 75°43'
$Z_{01} = Z_{20} = (Z_{0'1'} = Z_{2'0'})$	0.0116 < -166°52'	0.0094 < -39°28'	0.0257 < -63°25'	0.0241 < -72°14'
$Z_{02} = Z_{10} = (Z_{0'2'} = Z_{1'0'})$	< 5°8'	0.0153 < 28°53'	0.0197 < -94°58'	0.0217 < -100°20'
$Z_{12} = (Z_{1'2'})$	0.0255 < -40°9'	0.0275 < 147°26'	0.0276 < 161°17'	0.0281 < 149°46'
$Z_{21} = (Z_{2'1'})$	0.0256 < -139°1'	0.0275 < 27°29'	0.0277 < 37°13'	0.0282 < 29°6'
$(Z_{11'} = Z_{1'1} = Z_{22'} = Z_{2'2})$			0.0114 < 88°6'	0.0129 < 88°44'
$(Z_{02'} = Z_{0'2} = Z_{1'0} = Z_{10'})$			0.0140 < -93°44'	0.0185 < -91°16'
$(Z_{02'} = Z_{0'2} = Z_{1'0} = Z_{10'}$			0.0150 < -44°11'	0.0173 < -77°2'
$(Z_{1'2} = Z_{12'})$			0.0103 < 145°10'	0.0101 < 149°20'
$(Z_{21'} = Z_{2'1})$			0.0106 < 30°56'	0.0102 < 27°31'

Table A4.9:
Sequence self and mutual impedances for various lines

Consider an earthed, infinite busbar source behind a length of transmission line as shown in Figure A4.19(a). An earth fault involving phase A is assumed to occur at F. If the driving voltage is E and the fault current is I_a then the earth fault impedance is Z_e.

From symmetrical component theory (see Chapter [A3: Fault Calculations]):

$$I_a = \frac{3E}{Z_1 + Z_2 + Z_0}$$

thus

$$Z_e = \frac{2Z_1 + Z_0}{3}$$

since, as shown, $Z_1 = Z_2$ for a transmission circuit. From Equations A4.12, $Z_1 = Z_p - Z_m$ and $Z_0 = Z_p + 2Z_m$. Thus, substituting these values in the above equation gives $Z_e = Z_p$. This relation is physically valid because Z_p is the self-impedance of a single conductor with an earth return. Similarly, for a phase fault between phases B and C at F :

$$I_b = -I_c = \frac{\sqrt{3E}}{2Z_1}$$

where $\sqrt{3E}$ is the voltage between phases and $2Z$ is the impedance of the fault loop.

Making use of the above relations a transmission circuit may be represented, without any loss in generality, by the equivalent of Figure A4.19(b), where Z_1 is the phase impedance to the fault and $(Z_0-Z_1)/3$ is the impedance of the earth path, there being no mutual impedance between the phases or between phase and earth. The equivalent is valid for single and double circuit lines except that for double circuit lines there is zero sequence mutual impedance, hence $Z_0=(Z_{00} - Z_{0'0})$.

The equivalent circuit of Figure A4.19(b) is valuable in distance relay applications because the phase and earth fault relays are set to measure Z_2 and are compensated for the earth return impedance $(Z_0-Z_1)/3$.

It is customary to quote the impedances of a transmission circuit in terms of Z_1 and the ratio Z_0/Z_1, since in this form they are most directly useful. By definition, the positive sequence impedance Z_1 is a function of the conductor spacing and radius, whereas the Z_0/Z_1 ratio is dependent primarily on the level of earth resistivity ρ.

Further details may be found in Chapter [C4: Distance Protection Schemes].
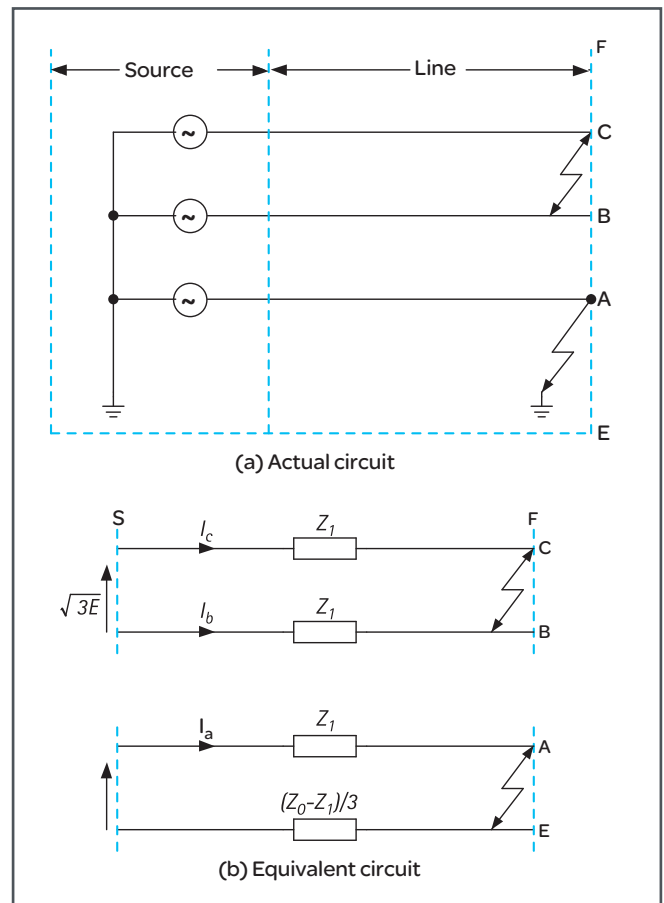
Figure A4.19:
Three-phase equivalent of a transmission circuit

23. Cable circuits

The basic formulae for calculating the series and shunt impedances of a transmission circuit, Equations A4.11 and A4.17, may be applied for evaluating cable parameters; since the conductor configuration is normally symmetrical, GMD and GMR values can be used without risk of appreciable errors. However, the formulae must be modified by the inclusion of empirical factors to take account of sheath and screen effects. A useful general reference on cable formulae is given in reference [Ref A4.4: Power System Analysis]; more detailed information on particular types of cables should be obtained direct from the manufacturers. The equivalent circuit for determining the positive and negative sequence series impedances of a cable is shown in Figure A4.20.
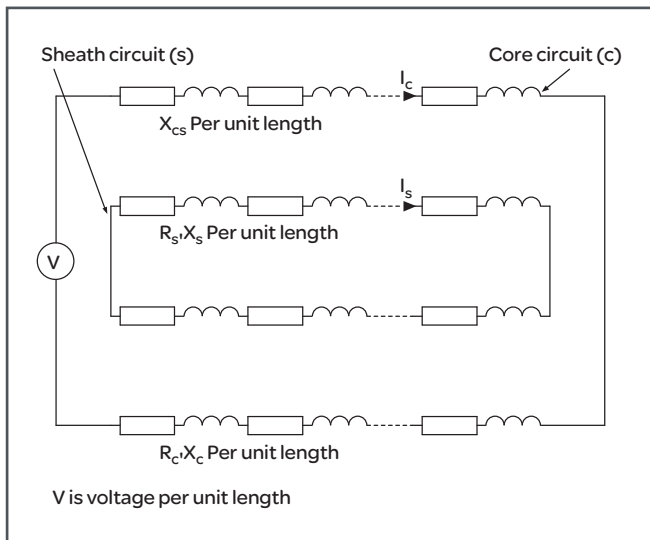
Figure A4.20:
Equivalent circuit for determining positive or negative impedance of cables

From this circuit it can be shown that:

$$Z_1 = Z_2 = \left\{ R_c + R_s \frac{X_{cs}^2}{R_s^2 + X_s^2} \right\}$$

$$+ j \left\{ X_c - X_s \frac{X_{cs}^2}{R_s^2 + X_s^2} \right\} \quad \text{...Equation A4.24}$$

where R_c and R_s are the core and sheath (screen) resistances per unit length, X_c and X_s core and sheath (screen) reactances per unit length and X_{cs} the mutual reactance between core and sheath (screen) per unit length. X_{cs} is in general equal to X_s.

The zero sequence series impedances are obtained directly using Equation A4.11 and account can be taken of the sheath in the same way as an earth wire in the case of an overhead line.

The shunt capacitances of a sheathed cable can be calculated from the simple formula:

$$C = 0.0241\varepsilon \left\{ \frac{1}{\log \frac{d+2T}{d}} \right\} \mu F/km$$

$$\text{...Equation A4.25}$$

where d is the overall diameter for a round conductor, T core insulation thickness and ε permittivity of dielectric. When the conductors are oval or shaped, an equivalent diameter d' may be used where $d' = (1/\pi)$ x periphery of conductor. No simple formula exists for belted or unscreened cables, but an empirical formula that gives reasonable results is:

$$C = \frac{0.0555\varepsilon}{G} \mu F/km$$

$$\text{...Equation A4.26}$$

where G is a geometric factor which is a function of core and belt insulation thickness and overall conductor diameter.

24. Overhead line and cable data   A4

The following tables contain typical data on overhead lines and cables that can be used in conjunction with the various equations quoted in this text. It is not intended that this data should replace that supplied by manufacturers. Where the results of calculations are important, reliance should not be placed on the data in these tables and data should be sourced directly from a manufacturer/supplier.

At the conceptual design stage, initial selection of overhead line conductor size will be determined by four factors:

a. maximum load to be carried in MVA

b. length of line

c. conductor material and hence maximum temperature

d. cost of losses

Table A4.20 gives indicative details of the capability of various sizes of overhead lines using the above factors, for AAAC (All

Aluminium Alloy Conductors) and ACSR (Aluminium Conductor Steel Reinforced) conductor materials. It is based on commonly used standards for voltage drop and ambient temperature. Since these factors may not be appropriate for any particular project, the table should only be used as a guide for initial sizing, with appropriately detailed calculations carried out to arrive at a final proposal.

Number of Layers	Number of Al Strands	GMR
1	6	0.5r *
1	12	0.75r *
2	18	0.776r
2	24	0.803r
2	26	0.812r
2	30	0.826r
2	32	0.833r
3	36	0.778r
3	45	0.794r
3	48	0.799r
3	54	0.81r
3	66	0.827r
4	72	0.789r
4	76	0.793r
4	84	0.801r

Note: Indicative values only, since GMR for single layer conductors is affected by cyclic magnetic flux, which depends on various factors.

Number of Strands	GMR
7	0.726r
19	0.758r
37	0.768r
61	0.772r
91	0.774r
127	0.776r
169	0.776r
Solid	0.779r

Table A4.10:
GMR for stranded copper, aluminium and aluminium alloy conductors (r = conductor radius)

Table A4.11:
GMR for aluminium conductor steel reinforced (ACSR)
(r = conductor radius)

A4

24. Overhead line and cable data

(a) ASTM (American Society for Testing and Materials) standards

Stranding area (mm²)	Wire	Overall diameter (mm)	R_{DC} diameter (mm)	(20°C) (Ω / km)
10.6	7	1.38	4.17	1.734
21.2	7	1.96	5.89	0.865
26.7	7	2.20	6.60	0.686
33.6	7	7.00	7.42	0.544
42.4	7	2.77	8.33	0.431
53.5	7	3.12	9.35	0.342
67.4	7	3.50	10.52	0.271
85.0	7	3.93	11.79	0.215
107.2	7	4.42	13.26	0.171
126.6	19	2.91	14.58	0.144
152.0	19	3.19	15.98	0.120
177.3	19	3.45	17.25	0.103
202.7	19	3.69	18.44	0.090
228.0	37	2.80	19.61	0.080
253.3	37	2.95	20.65	0.072
278.7	37	3.10	21.67	0.066
304.3	37	3.23	22.63	0.060
329.3	61	2.62	23.60	0.056
354.7	61	2.72	24.49	0.052
380.0	61	2.82	25.35	0.048
405.3	61	2.91	26.19	0.045
456.0	61	3.09	27.79	0.040
506.7	61	3.25	29.26	0.036

(b) BS (British Standards) standards

Stranding area (mm²)	Wire	Overall diameter (mm)	R_{DC} diameter (mm)	(20°C) (Ω / km)
11.0	1	3.73	3.25	1.617
13.0	1	4.06	4.06	1.365
14.0	1	4.22	4.22	1.269
14.5	7	1.63	4.88	1.231
16.1	1	4.52	4.52	1.103
18.9	1	4.90	4.90	0.938
23.4	1	5.46	5.46	0.756
32.2	1	6.40	6.40	0.549
38.4	7	2.64	7.92	0.466
47.7	7	2.95	8.84	0.375
65.6	7	3.45	10.36	0.273
70.1	1	9.45	9.45	0.252
97.7	7	4.22	12.65	0.183
129.5	19	2.95	14.73	0.139
132.1	7	4.90	14.71	0.135
164.0	7	5.46	16.38	0.109
165.2	19	3.33	16.64	0.109

Table A4.12:
Overhead line conductor - hard drawn copper

(a) to ASTM B232

Designation	Stranding and wire diameter (mm)				Sectional area (mm²)		Total area (mm²)	Approxi. overall diameter (mm)	RDC at 20°C (Ω / km)
	Aluminium		Steel		Aluminium	Steel			
Sparrow	6	2.67	1	2.67	33.6	5.6	39.2	8.01	0.854
Robin	6	3	1	3	42.4	7.1	49.5	9	0.677
Raven	6	3.37	1	3.37	53.5	8.9	62.4	10.11	0.536
Quail	6	3.78	1	3.78	67.4	11.2	78.6	11.34	0.426
Pigeon	6	4.25	1	4.25	85.0	14.2	99.2	12.75	0.337
Penguin	6	4.77	1	4.77	107.2	17.9	125.1	14.31	0.268
Partridge	26	2.57	7	2	135.2	22.0	157.2	16.28	0.214
Ostrich	26	2.73	7	2.21	152.0	26.9	178.9	17.28	0.191
Merlin	18	3.47	1	3.47	170.5	9.5	179.9	17.35	0.169
Lark	30	2.92	7	2.92	201.4	46.9	248.3	20.44	0.144
Hawk	26	3.44	7	2.67	241.7	39.2	280.9	21.79	0.120
Dove	26	3.72	7	2.89	282.0	45.9	327.9	23.55	0.103
Teal	30	3.61	19	2.16	306.6	69.6	376.2	25.24	0.095
Swift	36	3.38	1	3.38	322.3	9.0	331.2	23.62	0.089
Tern	45	3.38	7	2.25	402.8	27.8	430.7	27.03	0.072
Canary	54	3.28	7	3.28	456.1	59.1	515.2	29.52	0.064
Curlew	54	3.52	7	3.52	523.7	68.1	591.8	31.68	0.055
Finch	54	3.65	19	2.29	565.0	78.3	643.3	33.35	0.051
Bittern	45	4.27	7	2.85	644.5	44.7	689.2	34.17	0.045
Falcon	54	4.36	19	2.62	805.7	102.4	908.1	39.26	0.036
Kiwi	72	4.41	7	2.94	1100.0	47.5	1147.5	44.07	0.027

(b) to BS 215.2

Designation	Stranding and wire diameter (mm)				Sectional area (mm²)		Total area (mm²)	Approxi. overall diameter (mm)	RDC at 20°C (Ω / km)
	Aluminium		Steel		Aluminium	Steel			
Gopher	6	2.36	1	2.36	26.2	4.4	30.6	7.08	1.093
Weasel	6	2.59	1	2.59	31.6	5.3	36.9	7.77	0.908
Ferret	6	3	1	3	42.4	7.1	49.5	9	0.676
Rabbit	6	3.35	1	3.35	52.9	8.8	61.7	10.05	0.542
Horse	12	2.79	7	2.79	73.4	42.8	116.2	13.95	0.393
Dog	6	4.72	7	1.57	105.0	13.6	118.5	14.15	0.273
Tiger	30	2.36	7	2.36	131.2	30.6	161.9	16.52	0.220
Wolf	30	2.59	7	2.59	158.1	36.9	194.9	18.13	0.182
Dingo	18	3.35	1	3.35	158.7	8.8	167.5	16.75	0.181
Lynx	30	2.79	7	2.79	183.4	42.8	226.2	19.53	0.157
Caracal	18	3.61	1	3.61	184.2	10.2	194.5	18.05	0.156
Jaguar	18	3.86	1	3.86	210.6	11.7	222.3	19.3	0.137
Panther	30	3	7	3	212.1	49.5	261.5	21	0.136
Zebra	54	3.18	7	3.18	428.9	55.6	484.5	28.62	0.067

Table A4.13:
Overhead line conductor data - aluminium conductors steel reinforced (ACSR).

(c) to DIN 48204

Designation	Stranding and wire diameter (mm)				Sectional area (mm²)		Total area (mm²)	Approxi. overall diameter (mm)	RDC at 20°C (Ω/km)
	Aluminium		Steel		Aluminium	Steel			
35/6	6	2.7	1	2.7	34.4	5.7	40.1	8.1	0.834
44/32	14	2	7	2.4	44.0	31.7	75.6	11.2	0.652
50/8	6	3.2	1	3.2	48.3	8.0	56.3	9.6	0.594
70/12	26	1.85	7	1.44	69.9	11.4	81.3	11.7	0.413
95/15	26	2.15	7	1.67	94.4	15.3	109.7	13.6	0.305
95/55	12	3.2	7	3.2	96.5	56.3	152.8	16	0.299
120/70	12	3.6	7	3.6	122.1	71.3	193.4	18	0.236
150/25	26	2.7	7	2.1	148.9	24.2	173.1	17.1	0.194
170/40	30	2.7	7	2.7	171.8	40.1	211.8	18.9	0.168
185/30	26	3	7	2.33	183.8	29.8	213.6	19	0.157
210/50	30	3	7	3	212.1	49.5	261.5	21	0.136
265/35	24	3.74	7	2.49	263.7	34.1	297.7	22.4	0.109
305/40	54	2.68	7	2.68	304.6	39.5	344.1	24.1	0.095
380/50	54	3	7	3	381.7	49.5	431.2	27	0.076
550/70	54	3.6	7	3.6	549.7	71.3	620.9	32.4	0.052
560/50	48	3.86	7	3	561.7	49.5	611.2	32.2	0.051
650/45	45	4.3	7	2.87	653.5	45.3	698.8	34.4	0.044
1045/45	72	4.3	7	2.87	1045.6	45.3	1090.9	43	0.028

(a) ASTM

Standard	Designation	No. of Al strands	Wire diameter (mm)	Sectional area (mm2)	Overall diameter (mm)	R_{DC} at 20°C (Ω/km)
ASTM B-397	Kench	7	2.67	39.2	8.0	0.838
	Kibe	7	3.37	62.4	10.1	0.526
	Kayak	7	3.78	78.6	11.4	0.418
	Kopeck	7	4.25	99.3	12.8	0.331
	Kittle	7	4.77	125.1	14.3	0.262
	Radian	19	3.66	199.9	18.3	0.164
	Rede	19	3.78	212.6	18.9	0.155
	Ragout	19	3.98	236.4	19.9	0.140
	Rex	19	4.14	255.8	19.9	0.129
	Remex	19	4.36	283.7	21.8	0.116
	Ruble	19	4.46	296.8	22.4	0.111
	Rune	19	4.7	330.6	23.6	0.100
	Spar	37	3.6	376.6	25.2	0.087
	Solar	37	4.02	469.6	28.2	0.070
ASTM B-399	-	19	3.686	202.7	18.4	0.165
	-	19	3.909	228.0	19.6	0.147
	-	19	4.12	253.3	20.6	0.132
	-	37	3.096	278.5	21.7	0.120
	-	37	3.233	303.7	22.6	0.110
	-	37	3.366	329.2	23.6	0.102
	-	37	3.493	354.6	24.5	0.094
	-	37	3.617	380.2	25.3	0.088
	-	37	3.734	405.2	26.1	0.083
	-	37	3.962	456.2	27.7	0.073
	-	37	4.176	506.8	29.2	0.066

(d) to NF C34-120

Designation	Stranding and wire diameter (mm)				Sectional area (mm²)		Total area (mm²)	Approxi. overall diameter (mm)	RDC at 20°C (Ohm/km)
	Aluminium		Steel		Aluminium	Steel			
CANNA 59.7	12	2	7	2	37.7	22.0	59.7	10	0.765
CANNA 75.5	12	2.25	7	2.25	47.7	27.8	75.5	11.25	0.604
CANNA 93.3	12	2.5	7	2.5	58.9	34.4	93.3	12.5	0.489
CANNA 116.2	30	2	7	2	94.2	22.0	116.2	14	0.306
CROCUS 116.2	30	2	7	2	94.2	22.0	116.2	14	0.306
CANNA 147.1	30	2.25	7	2.25	119.3	27.8	147.1	15.75	0.243
CROCUS 181.6	30	2.5	7	2.5	147.3	34.4	181.6	17.5	0.197
CROCUS 228	30	2.8	7	2.8	184.7	43.1	227.8	19.6	0.157
CROCUS 297	36	2.8	19	2.25	221.7	75.5	297.2	22.45	0.131
CANNA 288	30	3.15	7	3.15	233.8	54.6	288.3	22.05	0.124
CROCUS 288	30	3.15	7	3.15	233.8	54.6	288.3	22.05	0.124
CROCUS 412	32	3.6	19	2.4	325.7	86.0	411.7	26.4	0.089
CROCUS 612	66	3.13	19	2.65	507.8	104.8	612.6	32.03	0.057
CROCUS 865	66	3.72	19	3.15	717.3	148.1	865.4	38.01	0.040

(b) BS

Standard	Designation	No. of Al strands	Wire diameter (mm)	Sectional area (mm2)	Overall diameter (mm)	R_{DC} at 20°C (Ω/km)
BS 3242	Box	7	1.85	18.8	5.6	1.750
	Acacia	7	2.08	23.8	6.2	1.384
	Almond	7	2.34	30.1	7.0	1.094
	Cedar	7	2.54	35.5	7.6	0.928
	Fir	7	2.95	47.8	8.9	0.688
	Hazel	7	3.3	59.9	9.9	0.550
	Pine	7	3.61	71.6	10.8	0.460
	Willow	7	4.04	89.7	12.1	0.367
	-	7	4.19	96.5	12.6	0.341
	-	7	4.45	108.9	13.4	0.302
	Oak	7	4.65	118.9	14.0	0.277
	Mullberry	19	3.18	150.9	15.9	0.219
	Ash	19	3.48	180.7	17.4	0.183
	Elm	19	3.76	211.0	18.8	0.157
	Poplar	37	2.87	239.4	20.1	0.139
	Sycamore	37	3.23	303.2	22.6	0.109
	Upas	37	3.53	362.1	24.7	0.092
	Yew	37	4.06	479.0	28.4	0.069
	Totara	37	4.14	498.1	29.0	0.067
	Rubus	61	3.5	586.9	31.5	0.057
	Araucaria	61	4.14	821.1	28.4	0.040

Table A4.13 (cont):
Overhead line conductor data - aluminium conductors steel reinforced (ACSR).

Table A4.14:
Overhead line conductor data - aluminium alloy.

24. Overhead line and cable data

(c) CSA (Canadian Standards Association)

Standard	Designation	No. of Al strands	Wire diameter (mm)	Sectional area (mm2)	Overall diameter (mm)	R_{DC} at 20°C (Ω/km)
CSA C49.1-M87	10	7	1.45	11.5	4.3	2.863
	16	7	1.83	18.4	5.5	1.788
	25	7	2.29	28.8	6.9	1.142
	40	7	2.89	46.0	8.7	0.716
	63	7	3.63	72.5	10.9	0.454
	100	19	2.78	115.1	13.9	0.287
	125	19	3.1	143.9	15.5	0.230
	160	19	3.51	184.2	17.6	0.180
	200	19	3.93	230.2	19.6	0.144
	250	19	4.39	287.7	22.0	0.115
	315	37	3.53	362.1	24.7	0.092
	400	37	3.98	460.4	27.9	0.072
	450	37	4.22	517.9	29.6	0.064
	500	37	4.45	575.5	31.2	0.058
	560	37	4.71	644.5	33.0	0.051
	630	61	3.89	725.0	35.0	0.046
	710	61	4.13	817.2	37.2	0.041
	800	61	4.38	920.8	39.5	0.036
	900	61	4.65	1035.8	41.9	0.032
	1000	91	4.01	1150.9	44.1	0.029
	1120	91	4.25	1289.1	46.7	0.026
	1250	91	4.49	1438.7	49.4	0.023
	1400	91	4.75	1611.3	52.2	0.021
	1500	91	4.91	1726.4	54.1	0.019

(e) NF (Association Francaise de Normalisation - AFNOR)

Standard	Designation	No. of Al strands	Wire diameter (mm)	Sectional area (mm2)	Overall diameter (mm)	R_{DC} at 20°C (Ω/km)
NF C34-125	ASTER 22	7	2	22.0	6.0	1.497
	ASTER 34-4	7	2.5	34.4	7.5	0.958
	ASTER 54-6	7	3.15	54.6	9.5	0.604
	ASTER 75-5	19	2.25	75.5	11.3	0.438
	ASTER 93,3	19	2.5	93.3	12.5	0.355
	ASTER 117	19	2.8	117.0	14.0	0.283
	ASTER 148	19	3.15	148.1	15.8	0.223
	ASTER 181-6	37	2.5	181.6	17.5	0.183
	ASTER 228	37	2.8	227.8	19.6	0.146
	ASTER 288	37	3.15	288.3	22.1	0.115
	ASTER 366	37	3.55	366.2	24.9	0.091
	ASTER 570	61	3.45	570.2	31.1	0.058
	ASTER 851	91	3.45	850.7	38.0	0.039
	ASTER 1144	91	4	1143.5	44.0	0.029
	ASTER 1600	127	4	1595.9	52.0	0.021

(d) DIN: (Deutsche Industrie Norm, Germany)

Standard	Designation	No. of Al strands	Wire diameter (mm)	Sectional area (mm2)	Overall diameter (mm)	R_{DC} at 20°C (Ω/km)
DIN 48201	16	7	1.7	15.9	5.1	2.091
	25	7	2.1	24.3	6.3	1.370
	35	7	2.5	34.4	7.5	0.967
	50	19	1.8	48.4	9.0	0.690
	50	7	3	49.5	9.0	0.672
	70	19	2.1	65.8	10.5	0.507
	95	19	2.5	93.3	12.5	0.358
	120	19	2.8	117.0	14.0	0.285
	150	37	2.25	147.1	15.7	0.228
	185	37	2.5	181.6	17.5	0.184
	240	61	2.25	242.5	20.2	0.138
	300	61	2.5	299.4	22.5	0.112
	400	61	2.89	400.1	26.0	0.084
	500	61	3.23	499.8	29.1	0.067

Table A4.14 (cont):
Overhead line conductor data - aluminium alloy.

24. Overhead line and cable data

(a) ASTM

Standard	Designation	Stranding and wire diameter (mm)				Sectional area (mm2)		Total area (mm2)	Approxi. overall diameter (mm)	R_{DC} at 20°C (Ω / km)
		Alloy		Steel		Alloy	Steel			
ASTM B711		26	2.62	7	2.04	140.2	22.9	163.1	7.08	0.240
		26	2.97	7	2.31	180.1	29.3	209.5	11.08	0.187
		30	2.76	7	2.76	179.5	41.9	221.4	12.08	0.188
		26	3.13	7	2.43	200.1	32.5	232.5	13.08	0.168
		30	3.08	7	3.08	223.5	52.2	275.7	16.08	0.151
		26	3.5	7	2.72	250.1	40.7	290.8	17.08	0.135
		26	3.7	7	2.88	279.6	45.6	325.2	19.08	0.120
		30	3.66	19	2.2	315.6	72.2	387.9	22.08	0.107
		30	3.88	19	2.33	354.7	81.0	435.7	24.08	0.095
		30	4.12	19	2.47	399.9	91.0	491.0	26.08	0.084
		54	3.26	19	1.98	450.7	58.5	509.2	27.08	0.075
		54	3.63	19	2.18	558.9	70.9	629.8	29.08	0.060
		54	3.85	19	2.31	628.6	79.6	708.3	30.08	0.054
		54	4.34	19	2.6	798.8	100.9	899.7	32.08	0.042
		84	4.12	19	2.47	1119.9	91.0	1210.9	35.08	0.030
		84	4.35	19	2.61	1248.4	101.7	1350.0	36.08	0.027

(b) DIN

Standard	Designation	Stranding and wire diameter (mm)				Sectional area (mm2)		Total area (mm2)	Approxi. overall diameter (mm)	R_{DC} at 20°C (Ω / km)
		Alloy		Steel		Alloy	Steel			
DIN 48206	70/12	26	1.85	7	1.44	69.9	11.4	81.3	11.7	0.479
	95/15	26	2.15	7	1.67	94.4	15.3	109.7	13.6	0.355
	125/30	30	2.33	7	2.33	127.9	29.8	157.8	16.3	0.262
	150/25	26	2.7	7	2.1	148.9	24.2	173.1	17.1	0.225
	170/40	30	2.7	7	2.7	171.8	40.1	211.8	18.9	0.195
	185/30	26	3	7	2.33	183.8	29.8	213.6	19	0.182
	210/50	30	3	7	3	212.1	49.5	261.5	21	0.158
	230/30	24	3.5	7	2.33	230.9	29.8	260.8	21	0.145
	265/35	24	3.74	7	2.49	263.7	34.1	297.7	22.4	0.127
	305/40	54	2.68	7	2.68	304.6	39.5	344.1	24.1	0.110
	380/50	54	3	7	3	381.7	49.5	431.2	27	0.088
	450/40	48	3.45	7	2.68	448.7	39.5	488.2	28.7	0.075
	560/50	48	3.86	7	3	561.7	49.5	611.2	32.2	0.060
	680/85	54	4	19	2.4	678.6	86.0	764.5	36	0.049

(c) NF

Standard	Designation	Stranding and wire diameter (mm)				Sectional area (mm2)		Total area (mm2)	Approxi. overall diameter (mm)	R_{DC} at 20°C (Ω / km)
		Alloy		Steel		Alloy	Steel			
NF C34-125	PHLOX 116.2	18	2	19	2	56.5	59.7	116.2	14	0.591
	PHLOX 147.1	18	2.25	19	2.25	71.6	75.5	147.1	15.75	0.467
	PASTEL 147.1	30	2.25	7	2.25	119.3	27.8	147.1	15.75	0.279
	PHLOX 181.6	18	2.5	19	2.5	88.4	93.3	181.6	17.5	0.378
	PASTEL 181.6	30	2.5	7	2.5	147.3	34.4	181.6	17.5	0.226
	PHLOX 228	18	2.8	19	2.8	110.8	117.0	227.8	19.6	0.300
	PASTEL 228	30	2.8	7	2.8	184.7	43.1	227.8	19.6	0.180
	PHLOX 288	18	3.15	19	3.15	140.3	148.1	288.3	22.05	0.238
	PASTEL 288	30	3.15	7	3.15	233.8	54.6	288.3	22.05	0.142
	PASTEL 299	42	2.5	19	2.5	206.2	93.3	299.4	22.45	0.162
	PHLOX 376	24	2.8	37	2.8	147.8	227.8	375.6	26.4	0.226

Table A4.15:
Overhead line conductor data - aluminium alloy conductors, steel re-inforced (AACSR)

A4

24. Overhead line and cable data

Sectional area of Aluminium mm²	R_{DC} at 20°C Ω/km	R_{DC} at 50 Hz @20°C Ω/km	X_{AC} at 50 Hz				X_{AC} at 50 Hz and shunt capacitance													
			3.3 kV Ω/km	6.6 kV Ω/km	11 kV Ω/km	22 kV Ω/km	33 kV		66 kV						132 kV					
									Rat circuit		Double vertical		Triangle		Double vertical		Double triangle		Rat circuit	
							X Ω/km	C nF/km	X Ω/km	C nF/km	X Ω/km	C nF/km	X Ω/km	C nF/km	X Ω/km	C nF/km	X Ω/km	C nF/km	X Ω/km	C nF/km
13.3	2.1586	2.159	0.395	0.409	0.420	0.434	0.445	8.7	0.503	7.6	0.513	7.4	0.520	7.3	0.541	7.0	0.528	7.2	0.556	6.8
15.3	1.8771	1.877	0.391	0.405	0.415	0.429	0.441	8.8	0.499	7.7	0.508	7.5	0.515	7.4	0.537	7.1	0.523	7.3	0.552	6.9
21.2	1.3557	1.356	0.381	0.395	0.405	0.419	0.430	9.0	0.488	7.8	0.498	7.7	0.505	7.6	0.527	7.2	0.513	7.4	0.542	7.0
23.9	1.2013	1.201	0.376	0.390	0.401	0.415	0.426	9.1	0.484	7.9	0.494	7.8	0.501	7.6	0.522	7.3	0.509	7.5	0.537	7.1
26.2	1.0930	1.093	0.374	0.388	0.398	0.412	0.424	9.2	0.482	8.0	0.491	7.8	0.498	7.7	0.520	7.3	0.506	7.5	0.535	7.1
28.3	1.0246	1.025	0.352	0.366	0.377	0.391	0.402	9.4	0.460	8.2	0.470	8.0	0.477	7.8	0.498	7.5	0.485	7.7	0.513	7.3
33.6	0.8535	0.854	0.366	0.380	0.390	0.404	0.416	9.4	0.474	8.1	0.484	7.9	0.491	7.8	0.512	7.5	0.499	7.7	0.527	7.2
37.7	0.7647	0.765	0.327	0.341	0.351	0.365	0.376	9.7	0.435	8.4	0.444	8.2	0.451	8.1	0.473	7.7	0.459	7.9	0.488	7.4
42.4	0.6768	0.677	0.359	0.373	0.383	0.397	0.409	9.6	0.467	8.3	0.476	8.1	0.483	7.9	0.505	7.6	0.491	7.8	0.520	7.3
44.0	0.6516	0.652	0.320	0.334	0.344	0.358	0.369	9.9	0.427	8.5	0.437	8.3	0.444	8.2	0.465	7.8	0.452	8.0	0.481	7.5
47.7	0.6042	0.604	0.319	0.333	0.344	0.358	0.369	9.9	0.427	8.5	0.437	8.3	0.444	8.2	0.465	7.8	0.452	8.1	0.480	7.6
51.2	0.5634	0.564	0.317	0.331	0.341	0.355	0.367	10.0	0.425	8.6	0.434	8.4	0.441	8.2	0.463	7.9	0.449	8.1	0.478	7.6
58.9	0.4894	0.490	0.313	0.327	0.337	0.351	0.362	10.1	0.421	8.7	0.430	8.5	0.437	8.3	0.459	7.9	0.445	8.2	0.474	7.7
63.1	0.4545	0.455	0.346	0.360	0.371	0.385	0.396	9.9	0.454	8.5	0.464	8.3	0.471	8.2	0.492	7.8	0.479	8.0	0.507	7.5
67.4	0.4255	0.426	0.344	0.358	0.369	0.383	0.394	10.0	0.452	8.5	0.462	8.3	0.469	8.2	0.490	7.8	0.477	8.1	0.505	7.6
73.4	0.3930	0.393	0.306	0.320	0.330	0.344	0.356	10.3	0.414	8.8	0.423	8.6	0.430	8.5	0.452	8.1	0.438	8.3	0.467	7.8
79.2	0.3622	0.362	0.339	0.353	0.363	0.377	0.389	10.1	0.447	8.7	0.457	8.4	0.464	8.3	0.485	7.9	0.472	8.2	0.500	7.6
85.0	0.3374	0.338	0.337	0.351	0.361	0.375	0.387	10.2	0.445	8.7	0.454	8.5	0.461	8.4	0.483	7.9	0.469	8.2	0.498	7.7
94.4	0.3054	0.306	0.302	0.316	0.327	0.341	0.352	10.3	0.410	8.8	0.420	8.6	0.427	8.4	0.448	8.0	0.435	8.3	0.463	7.8
105.0	0.2733	0.274	0.330	0.344	0.355	0.369	0.380	10.4	0.438	8.8	0.448	8.6	0.455	8.5	0.476	8.1	0.463	8.3	0.491	7.8
121.6	0.2371	0.237	0.294	0.308	0.318	0.332	0.344	10.6	0.402	9.0	0.412	8.8	0.419	8.6	0.440	8.2	0.427	8.4	0.455	7.9
127.9	0.2254	0.226	0.290	0.304	0.314	0.328	0.340	10.7	0.398	9.0	0.407	8.8	0.414	8.7	0.436	8.2	0.422	8.5	0.451	8.0
131.2	0.2197	0.220	0.289	0.303	0.313	0.327	0.339	10.7	0.397	9.1	0.407	8.8	0.414	8.7	0.435	8.3	0.421	8.5	0.450	8.0
135.2	0.2133	0.214	0.297	0.311	0.322	0.336	0.347	10.5	0.405	9.0	0.415	8.8	0.422	8.6	0.443	8.2	0.430	8.4	0.458	7.9
148.9	0.1937	0.194	0.288	0.302	0.312	0.326	0.338	10.8	0.396	9.1	0.406	8.9	0.413	8.7	0.434	8.3	0.420	8.6	0.449	8.0
158.7	0.1814	0.182	0.292	0.306	0.316	0.330	0.342	10.7	0.400	9.1	0.410	8.9	0.417	8.7	0.438	8.3	0.425	8.5	0.453	8.0
170.5	0.1691	0.170	0.290	0.304	0.314	0.328	0.340	10.8	0.398	9.1	0.407	8.9	0.414	8.8	0.436	8.3	0.422	8.6	0.451	8.0
184.2	0.1565	0.157	0.287	0.302	0.312	0.326	0.337	10.9	0.395	9.2	0.405	9.0	0.412	8.8	0.433	8.4	0.420	8.6	0.449	8.1
201.4	0.1438	0.144	0.280	0.294	0.304	0.318	0.330	11.0	0.388	9.3	0.398	9.1	0.405	8.9	0.426	8.5	0.412	8.8	0.441	8.2
210.6	0.1366	0.137	0.283	0.297	0.308	0.322	0.333	11.0	0.391	9.3	0.401	9.1	0.408	8.9	0.429	8.4	0.416	8.7	0.444	8.1
221.7	0.1307	0.131	0.274	0.288	0.298	0.312	0.323	11.3	0.381	9.5	0.391	9.3	0.398	9.1	0.419	8.6	0.406	8.9	0.435	8.3
230.9	0.1249	0.126	0.276	0.290	0.300	0.314	0.326	11.2	0.384	9.4	0.393	9.2	0.400	9.0	0.422	8.6	0.408	8.9	0.437	8.3
241.7	0.1193	0.120	0.279	0.293	0.303	0.317	0.329	11.2	0.387	9.4	0.396	9.2	0.403	9.0	0.425	8.5	0.411	8.8	0.440	8.2
263.7	0.1093	0.110	0.272	0.286	0.296	0.310	0.321	11.3	0.380	9.5	0.389	9.3	0.396	9.1	0.418	8.6	0.404	8.9	0.433	8.3
282.0	0.1022	0.103	0.274	0.288	0.298	0.312	0.324	11.3	0.382	9.5	0.392	9.3	0.399	9.1	0.420	8.6	0.406	8.9	0.435	8.3
306.6	0.0945	0.095	0.267	0.281	0.291	0.305	0.317	11.5	0.375	9.7	0.384	9.4	0.391	9.2	0.413	8.7	0.399	9.1	0.428	8.4
322.3	0.0895	0.090	0.270	0.284	0.294	0.308	0.320	11.5	0.378	9.6	0.387	9.4	0.394	9.2	0.416	8.7	0.402	9.0	0.431	8.4
339.3	0.085	0.086	0.265	0.279	0.289	0.303	0.315	11.6	0.373	9.7	0.383	9.5	0.390	9.3	0.411	8.8	0.398	9.1	0.426	8.5
362.6	0.0799	0.081	0.262	0.276	0.286	0.300	0.311	11.7	0.369	9.8	0.379	9.6	0.386	9.4	0.408	8.9	0.394	9.2	0.423	8.5
386.0	0.0747	0.076	0.261	0.275	0.285	0.299	0.311	11.8	0.369	9.8	0.379	9.6	0.386	9.4	0.407	8.9	0.393	9.2	0.422	8.6
402.8	0.0719	0.073	0.261	0.275	0.285	0.299	0.310	11.8	0.368	9.9	0.378	9.6	0.385	9.4	0.407	8.9	0.393	9.2	0.422	8.6
428.9	0.0671	0.068	0.267	0.281	0.291	0.305	0.316	11.5	0.374	9.7	0.384	9.4	0.391	9.2	0.413	8.7	0.399	9.0	0.428	8.4
448.7	0.0642	0.066	0.257	0.271	0.281	0.295	0.306	11.9	0.364	10.0	0.374	9.7	0.381	9.5	0.402	9.0	0.389	9.3	0.418	8.7
456.1	0.0635	0.065	0.257	0.271	0.281	0.295	0.307	12.0	0.365	10.0	0.374	9.7	0.381	9.5	0.403	9.0	0.389	9.3	0.418	8.7
483.4	0.0599	0.061	0.255	0.269	0.279	0.293	0.305	12.0	0.363	10.0	0.372	9.8	0.379	9.6	0.401	9.0	0.387	9.4	0.416	8.7
494.4	0.0583	0.060	0.254	0.268	0.279	0.293	0.304	12.1	0.362	10.0	0.372	9.8	0.379	9.6	0.400	9.0	0.387	9.4	0.415	8.7
510.5	0.0565	0.058	0.252	0.266	0.277	0.291	0.302	12.1	0.360	10.1	0.370	9.8	0.377	9.6	0.398	9.1	0.385	9.4	0.413	8.7
523.7	0.0553	0.057	0.252	0.266	0.277	0.291	0.302	12.1	0.360	10.1	0.370	9.8	0.377	9.6	0.398	9.1	0.385	9.4	0.413	8.7

Table A4.16:
Feeder circuits data - overhead lines at 50Hz

24. Overhead line and cable data **A4**

Sectional area of Aluminium mm²	R_DC at 20°C Ω/km	R_DC at 50 Hz @20°C Ω/km	X_AC at 60 Hz 3.3 kV Ω/km	X_AC at 60 Hz 6.6 kV Ω/km	X_AC at 60 Hz 11 kV Ω/km	X_AC at 60 Hz 22 kV Ω/km	33 kV X Ω/km	33 kV C nF/km	66 kV Rat circuit X Ω/km	66 kV Rat circuit C nF/km	66 kV Double vertical X Ω/km	66 kV Double vertical C nF/km	66 kV Triangle X Ω/km	66 kV Triangle C nF/km	132 kV Double vertical X Ω/km	132 kV Double vertical C nF/km	132 kV Double triangle X Ω/km	132 kV Double triangle C nF/km	132 kV Rat circuit X Ω/km	132 kV Rat circuit C nF/km
13.3	2.1586	2.159	0.474	0.491	0.503	0.520	0.534	8.7	0.604	7.6	0.615	7.4	0.624	7.3	0.649	7.0	0.633	7.2	0.668	6.8
15.3	1.8771	1.877	0.469	0.486	0.498	0.515	0.529	8.8	0.598	7.7	0.610	7.5	0.619	7.4	0.644	7.1	0.628	7.3	0.662	6.9
21.2	1.3557	1.356	0.457	0.474	0.486	0.503	0.516	9.0	0.586	7.8	0.598	7.7	0.606	7.6	0.632	7.2	0.616	7.4	0.650	7.0
23.9	1.2013	1.201	0.452	0.469	0.481	0.498	0.511	9.1	0.581	7.9	0.593	7.8	0.601	7.6	0.627	7.3	0.611	7.5	0.645	7.1
26.2	1.0930	1.093	0.449	0.466	0.478	0.495	0.508	9.2	0.578	8.0	0.590	7.8	0.598	7.7	0.624	7.3	0.608	7.5	0.642	7.1
28.3	1.0246	1.025	0.423	0.440	0.452	0.469	0.483	9.4	0.552	8.2	0.564	8.0	0.572	7.8	0.598	7.5	0.582	7.7	0.616	7.3
33.6	0.8535	0.854	0.439	0.456	0.468	0.485	0.499	9.4	0.569	8.1	0.580	7.9	0.589	7.8	0.614	7.5	0.598	7.7	0.633	7.2
37.7	0.7647	0.765	0.392	0.409	0.421	0.438	0.452	9.7	0.521	8.4	0.533	8.2	0.541	8.1	0.567	7.7	0.551	7.9	0.585	7.4
42.4	0.6768	0.677	0.431	0.447	0.460	0.477	0.490	9.6	0.560	8.3	0.572	8.1	0.580	7.9	0.606	7.6	0.589	7.8	0.624	7.3
44.0	0.6516	0.652	0.384	0.400	0.413	0.429	0.443	9.9	0.513	8.5	0.525	8.3	0.533	8.2	0.559	7.8	0.542	8.0	0.577	7.5
47.7	0.6042	0.604	0.383	0.400	0.412	0.429	0.443	9.9	0.513	8.5	0.524	8.3	0.533	8.2	0.558	7.8	0.542	8.1	0.576	7.6
51.2	0.5634	0.564	0.380	0.397	0.409	0.426	0.440	10.0	0.510	8.6	0.521	8.4	0.530	8.2	0.555	7.9	0.539	8.1	0.573	7.6
58.9	0.4894	0.490	0.375	0.392	0.404	0.421	0.435	10.1	0.505	8.7	0.516	8.5	0.525	8.3	0.550	7.9	0.534	8.2	0.568	7.7
63.1	0.4545	0.455	0.416	0.432	0.445	0.462	0.475	9.9	0.545	8.5	0.557	8.3	0.565	8.2	0.591	7.8	0.574	8.0	0.609	7.5
67.4	0.4255	0.426	0.413	0.430	0.442	0.459	0.473	10.0	0.543	8.5	0.554	8.3	0.563	8.2	0.588	7.8	0.572	8.1	0.606	7.6
73.4	0.3930	0.393	0.367	0.384	0.396	0.413	0.427	10.3	0.496	8.8	0.508	8.6	0.516	8.5	0.542	8.1	0.526	8.3	0.560	7.8
79.2	0.3622	0.362	0.407	0.424	0.436	0.453	0.467	10.1	0.536	8.7	0.548	8.4	0.556	8.3	0.582	7.9	0.566	8.2	0.600	7.6
85.0	0.3374	0.338	0.404	0.421	0.433	0.450	0.464	10.2	0.534	8.7	0.545	8.5	0.554	8.4	0.579	7.9	0.563	8.2	0.598	7.7
94.4	0.3054	0.306	0.363	0.380	0.392	0.409	0.423	10.3	0.492	8.8	0.504	8.6	0.512	8.4	0.538	8.0	0.522	8.3	0.556	7.8
105.0	0.2733	0.274	0.396	0.413	0.426	0.442	0.456	10.4	0.526	8.8	0.537	8.6	0.546	8.5	0.572	8.1	0.555	8.3	0.590	7.8
121.6	0.2371	0.238	0.353	0.370	0.382	0.399	0.413	10.6	0.482	9.0	0.494	8.8	0.502	8.6	0.528	8.2	0.512	8.4	0.546	7.9
127.9	0.2254	0.226	0.348	0.365	0.377	0.394	0.408	10.7	0.477	9.0	0.489	8.8	0.497	8.7	0.523	8.2	0.507	8.5	0.541	8.0
131.2	0.2197	0.220	0.347	0.364	0.376	0.393	0.407	10.7	0.476	9.1	0.488	8.8	0.496	8.7	0.522	8.3	0.506	8.5	0.540	8.0
135.2	0.2133	0.214	0.357	0.374	0.386	0.403	0.416	10.5	0.486	9.0	0.498	8.8	0.506	8.6	0.532	8.2	0.516	8.4	0.550	7.9
148.9	0.1937	0.194	0.346	0.362	0.375	0.392	0.405	10.8	0.475	9.1	0.487	8.9	0.495	8.7	0.521	8.3	0.504	8.6	0.539	8.0
158.7	0.1814	0.182	0.351	0.367	0.380	0.397	0.410	10.7	0.480	9.1	0.492	8.9	0.500	8.7	0.526	8.3	0.509	8.6	0.544	8.0
170.5	0.1691	0.170	0.348	0.365	0.377	0.394	0.408	10.8	0.477	9.1	0.489	8.9	0.497	8.8	0.523	8.3	0.507	8.6	0.541	8.0
184.2	0.1565	0.157	0.345	0.362	0.374	0.391	0.405	10.9	0.474	9.2	0.486	9.0	0.494	8.8	0.520	8.4	0.504	8.6	0.538	8.1
201.4	0.1438	0.145	0.336	0.353	0.365	0.382	0.396	11.0	0.466	9.3	0.477	9.1	0.486	8.9	0.511	8.5	0.495	8.8	0.529	8.2
210.6	0.1366	0.137	0.340	0.357	0.369	0.386	0.400	11.0	0.469	9.3	0.481	9.1	0.489	8.9	0.515	8.4	0.499	8.7	0.533	8.1
221.7	0.1307	0.132	0.328	0.345	0.357	0.374	0.388	11.3	0.458	9.5	0.469	9.3	0.478	9.1	0.503	8.6	0.487	8.9	0.522	8.3
230.9	0.1249	0.126	0.331	0.348	0.360	0.377	0.391	11.2	0.460	9.4	0.472	9.2	0.480	9.0	0.506	8.6	0.532	8.9	0.524	8.3
241.7	0.1193	0.120	0.335	0.351	0.364	0.381	0.394	11.2	0.464	9.4	0.476	9.2	0.484	9.0	0.510	8.5	0.493	8.8	0.528	8.2
263.7	0.1093	0.110	0.326	0.343	0.355	0.372	0.386	11.3	0.455	9.5	0.467	9.3	0.476	9.1	0.501	8.6	0.485	8.9	0.519	8.3
282.0	0.1022	0.103	0.329	0.346	0.358	0.375	0.389	11.3	0.458	9.5	0.470	9.3	0.478	9.1	0.504	8.6	0.488	8.9	0.522	8.3
306.6	0.0945	0.096	0.320	0.337	0.349	0.366	0.380	11.5	0.450	9.7	0.461	9.4	0.470	9.2	0.495	8.7	0.479	9.1	0.514	8.4
322.3	0.0895	0.091	0.324	0.341	0.353	0.370	0.384	11.5	0.453	9.6	0.465	9.4	0.473	9.2	0.499	8.7	0.483	9.0	0.517	8.4
339.3	0.0850	0.086	0.318	0.335	0.347	0.364	0.378	11.6	0.448	9.7	0.459	9.5	0.468	9.3	0.493	8.8	0.477	9.1	0.511	8.5
362.6	0.0799	0.081	0.314	0.331	0.343	0.360	0.374	11.7	0.443	9.8	0.455	9.6	0.463	9.4	0.489	8.9	0.473	9.2	0.507	8.5
386.0	0.0747	0.076	0.313	0.330	0.342	0.359	0.373	11.8	0.443	9.8	0.454	9.6	0.463	9.4	0.488	8.9	0.472	9.2	0.506	8.6
402.8	0.0719	0.074	0.313	0.330	0.342	0.359	0.372	11.8	0.442	9.9	0.454	9.6	0.462	9.4	0.488	8.9	0.472	9.2	0.506	8.6
428.9	0.0671	0.069	0.320	0.337	0.349	0.366	0.380	11.5	0.449	9.7	0.461	9.4	0.469	9.2	0.495	8.7	0.479	9.0	0.513	8.4
448.7	0.0642	0.066	0.308	0.325	0.337	0.354	0.367	11.9	0.437	10.0	0.449	9.7	0.457	9.5	0.483	9.0	0.467	9.3	0.501	8.7
456.1	0.0635	0.065	0.305	0.322	0.334	0.351	0.364	12.0	0.434	10.0	0.446	9.7	0.454	9.6	0.480	9.0	0.463	9.4	0.498	8.7
483.4	0.0599	0.062	0.306	0.323	0.335	0.352	0.366	12.0	0.435	10.0	0.447	9.8	0.455	9.6	0.481	9.0	0.465	9.4	0.499	8.7
494.4	0.0583	0.060	0.305	0.322	0.334	0.351	0.365	12.1	0.435	10.0	0.446	9.8	0.455	9.6	0.480	9.0	0.464	9.4	0.498	8.7
510.5	0.0565	0.059	0.303	0.320	0.332	0.349	0.362	12.1	0.432	10.1	0.444	9.8	0.452	9.6	0.478	9.1	0.462	9.4	0.496	8.7
523.7	0.0553	0.057	0.303	0.320	0.332	0.349	0.363	12.1	0.432	10.1	0.444	9.8	0.452	9.6	0.478	9.1	0.462	9.4	0.496	8.7

Table A4.16 (cont):
Feeder circuits data - overhead lines at 60Hz

24. Overhead line and cable data

		Conductor size (mm2)																
		25	35	50	70	95	120	150	185	240	300	400	500*	630*	800*	1000*	1200*	1600*
3.3kV	Series Resistance R (Ω/km)	0.927	0.669	0.494	0.342	0.247	0.196	0.158	0.127	0.098	0.08	0.064	0.051	0.042				
	Series Reactance X (Ω/km)	0.097	0.092	0.089	0.083	0.08	0.078	0.076	0.075	0.073	0.072	0.071	0.088	0.086				
	Susceptance ωC (mS/km)	0.059	0.067	0.079	0.09	0.104	0.111	0.122	0.133	0.146	0.16	0.179	0.19	0.202				
6.6kV	Series Resistance R (Ω/km)	0.927	0.669	0.494	0.342	0.247	0.196	0.158	0.127	0.098	0.08	0.064	0.057	0.042				
	Series Reactance X (Ω/km)	0.121	0.113	0.108	0.102	0.096	0.093	0.091	0.088	0.086	0.085	0.083	0.088	0.086				
	Susceptance ωC (mS/km)	0.085	0.095	0.104	0.12	0.136	0.149	0.16	0.177	0.189	0.195	0.204	0.205	0.228				
11kV	Series Resistance R (Ω/km)	0.927	0.669	0.494	0.342	0.247	0.196	0.158	0.127	0.098	0.08	0.064	0.051	0.042				
	Series Reactance X (Ω/km)	0.128	0.119	0.114	0.107	0.101	0.098	0.095	0.092	0.089	0.087	0.084	0.089	0.086				
	Susceptance ωC (mS/km)	0.068	0.074	0.082	0.094	0.105	0.115	0.123	0.135	0.15	0.165	0.182	0.194	0.216				
22kV	Series Resistance R (Ω/km)		0.669	0.494	0.348	0.247	0.196	0.158	0.127	0.098	0.08	0.064	0.051	0.042				
	Series Reactance X (Ω/km)		0.136	0.129	0.121	0.114	0.11	0.107	0.103	0.1	0.094	0.091	0.096	0.093				
	Susceptance ωC (mS/km)		0.053	0.057	0.065	0.072	0.078	0.084	0.091	0.1	0.109	0.12	0.128	0.141				
33kV	Series Resistance R (Ω/km)		0.669	0.494	0.348	0.247	0.196	0.158	0.127	0.098	0.08	0.064	0.051	0.042				
	Series Reactance X (Ω/km)		0.15	0.143	0.134	0.127	0.122	0.118	0.114	0.109	0.105	0.102	0.103	0.1				
	Susceptance ωC (mS/km)		0.042	0.045	0.05	0.055	0.059	0.063	0.068	0.075	0.081	0.089	0.094	0.103				
66kV*	Series Resistance R (Ω/km)												0.0387	0.031	0.0254	0.0215		
	Series Reactance X (Ω/km)												0.117	0.113	0.109	0.102		
	Susceptance ωC (mS/km)												0.079	0.082	0.088	0.11		
145kV*	Series Resistance R (Ω/km)												0.0387	0.031	0.0254	0.0215		
	Series Reactance X (Ω/km)												0.13	0.125	0.12	0.115		
	Susceptance ωC (mS/km)												0.053	0.06	0.063	0.072		
245kV*	Series Resistance R (Ω/km)											0.0487	0.0387	0.0310	0.0254	0.0215	0.0161	0.0126
	Series Reactance X (Ω/km)											0.145	0.137	0.134	0.128	0.123	0.119	0.113
	Susceptance ωC (mS/km)											0.044	0.047	0.05	0.057	0.057	0.063	0.072
420kV*	Series Resistance R (Ω/km)												0.0310	0.0254	0.0215	0.0161	0.0126	
	Series Reactance X (Ω/km)												0.172	0.162	0.156	0.151	0.144	
	Susceptance ωC (mS/km)												0.04	0.047	0.05	0.057	0.063	

For aluminium conductors of the same cross-section, the resistance increases by 60-65 percent, the series reactance and shunt capacitance are virtually unaltered.
* - single core cables in trefoil.
Different values apply if laid in spaced flat formation.
Series resistance - a.c. resistance @ 90°C. Series reactance - equivalent star reactance.
Data for 245kV and 420kV cables may vary significantly from that given, dependent on manufacturer and construction.

Table A4.17:
Characteristics of polyethylene insulated cables (XLPE)

24. Overhead line and cable data A4

		Conductor size (mm2)																
		10	16	25	35	50	70	95	120	150	185	240	300	400	500*	630*	800*	1000*
3.3kV	Series Resistance R (Ω/km)	2063	1289	825.5	595	439.9	304.9	220.4	174.5	142.3	113.9	87.6	70.8	56.7	45.5	37.1	31.2	27.2
	Series Reactance X (Ω/km)	87.7	83.6	76.7	74.8	72.5	70.2	67.5	66.6	65.7	64.7	63.8	62.9	62.4	73.5	72.1	71.2	69.8
	Susceptance ωC (mS/km)																	
6.6kV	Series Resistance R (Ω/km)	514.2	326	206.4	148.8	110	76.2	55.1	43.6	35.6	28.5	21.9	17.6	14.1	11.3	9.3	7.8	6.7
	Series Reactance X (Ω/km)	26.2	24.3	22	21.2	20.4	19.6	18.7	18.3	17.9	17.6	17.1	16.9	16.5	18.8	18.4	18	17.8
	Susceptance ωC (mS/km)																	
11kV	Series Resistance R (Ω/km)		111	0.87	0.63	0.46	0.32	0.23	0.184	0.15	0.12	0.092	0.074	0.059	0.048	0.039	0.033	0.028
	Series Reactance X (Ω/km)		9.26	0.107	0.1	0.096	0.091	0.087	0.085	0.083	0.081	0.079	0.077	0.076	0.085	0.083	0.081	0.08
	Susceptance ωC (mS/km)																	
22kV	Series Resistance R (Ω/km)			17.69	12.75	9.42	6.53	4.71	3.74	3.04	2.44	1.87	1.51	1.21	0.96	0.79	0.66	0.57
	Series Reactance X (Ω/km)			2.89	2.71	2.6	2.46	2.36	2.25	2.19	2.11	2.04	1.97	1.92	1.9	1.84	1.8	1.76
	Susceptance ωC (mS/km)																	
33kV	Series Resistance R (Ω/km)					4.19	2.9	2.09	0.181	0.147	0.118	0.09	0.073	0.058	0.046	0.038	0.031	0.027
	Series Reactance X (Ω/km)					1.16	1.09	1.03	0.107	0.103	0.101	0.097	0.094	0.09	0.098	0.097	0.092	0.089
	Susceptance ωC (mS/km)								0.104	0.116	0.124	0.194	0.151	0.281	0.179	0.198	0.22	0.245

Cables are of the solid type, 3 core except for those marked *. Impedances at 50Hz frequency

Table A4.18:
Characteristics of paper insulated cables

Conductor size (mm2)	3.3kV	
	R Ω/km	X Ω/km
16	1.380	0.106
25	0.870	0.100
35	0.627	0.094
50	0.463	0.091
70	0.321	0.086
95	0.232	0.084
120	0.184	0.081
150	0.150	0.079
185	0.121	0.077
240	0.093	0.076
300	0.075	0.075
400	0.060	0.075
500*	0.049	0.089
630*	0.041	0.086
800*	0.035	0.086
1000*	0.030	0.084

3 core copper conductors, 50Hz values
* - single core cables in trefoil

Table A4.19:
3.3 kV PVC insulated cables

A4

24. Overhead line and cable data

Voltage level		Cross Sectional area (mm²)	Conductors per phase	Surge Impedance loading	Voltage Drop loading	Indicative Thermal loading	
U$_n$ kV	U$_m$ kV			MVA	MWkm	MV	A
11	12	30	1	0.3	11	2.9	151
		50	1	0.3	17	3.9	204
		90	1	0.4	23	5.1	268
		120	1	0.5	27	6.2	328
		150	1	0.5	30	7.3	383
24	30	1	1.2	44	5.8	151	
		50	1	1.2	66	7.8	204
		90	1	1.2	92	10.2	268
		120	1	1.4	106	12.5	328
		150	1	1.5	119	14.6	383
33	36	50	1	2.7	149	11.7	204
		90	1	2.7	207	15.3	268
		120	1	3.1	239	18.7	328
		150	1	3.5	267	21.9	383
66	72.5	90	1	11	827	41	268
		150	1	11	1068	59	383
		250	1	11	1240	77	502
		250	2	15	1790	153	1004
132	145	150	1	44	4070	85	370
		250	1	44	4960	115	502
		250	2	58	7160	230	1004
		400	1	56	6274	160	698
		400	2	73	9057	320	1395
220	245	400	1	130	15600	247	648
		400	2	184	22062	494	1296
		400	4	260	31200	988	2592
380	420	400	2	410	58100	850	1296
		400	4	582	82200	1700	2590
		550	2	482	68200	1085	1650
		550	3	540	81200	1630	2475

Table A4.20:
OHL capabilities

25. References A4

[A4.1] Physical significance of sub-subtransient quantities in dynamic behaviour of synchronous machines.
I.M. Canay.
Proc. IEE, Vol. 135, Pt. B, November 1988.

[A4.2] IEC 60034-4.
Methods for determining synchronous machine quantities from tests.

[A4.3] IEEE Standards 115/115A.
IEEE Test Procedures for Synchronous Machines.

[A4.4] Power System Analysis.
J.R.Mortlock and M.W.Humphrey Davies
(Chapman & Hall, London).