Symmetrical short-circuit fault

The overwhelming proportion of short-circuit faults are on the network being fed by the generator and not internal or terminal short-circuit in the generator itself/

The behaviour under short circuit conditions depends on many factors:

- Location of fault and the effective impedance up to the fault
- The phase windings involved in the fault
- The instant of the cycle at which the fault occurs
- Any change in the prime-move speed
- The control response of the turbine governor, the AVR or the protection system
- The generator loading and excitation prior to the fault

Symmetrical short-circuits, i.e. across all 3 phases simultaneously are only one type of fault, others such as asymmetrical faults in one-phase only are more complex (but have the same underlying causes)

It is useful to consider the short-circuit as arising in 3 distinct intervals

Sub-transient – first few cycles

Transient – typically 1-2s in a large generator

Steady-state – usually cut-short by intervention of protection system

Concept of constant linkage

- Consider a coil subjected to a short-circuit fault
- Assuming an idealised coil with true zero impedance
- There can be no net emf induced in the short-circuited coil it as this would imply infinite current would flow
- Therefore there cannot be any rate of change in flux linkage within the coil
- Hence the flux-linkage remains at it pre fault value – at least in a zero impedance coil
- A practical coil has a small but finite impedance under short-circuit conditions
- However, in such cases, the constant linkage approximation is a useful, is a slightly idealised, starting point
- During the initial stage of the fault (first few cycles) the current dictated largely by consideration of constant flux linkage

Neglecting **resistance**, the short-circuit current is given by:

$$i_a = v_q\left[\frac{1}{x_d'}\cos(\omega_1 t+\theta_0) - \frac{x_{sq}+x_d'}{2x_d' x_{sq}} cos\theta_0 - \frac{x_{sq}-x_d'}{2x_d' x_{sq}} cos(2\omega_1 t+\theta_0)\right]$$

Fundamental AC component

DC component

Double frequency AC component

x_d' is the sub-transient d-axis reactance and is given by:

$$x_d' = \frac{x_{ad}x_f}{x_{ad}+x_f} + x$$

x_f field reactance

For full derivation see MG Say, 'Alternating Current Machines'

x_{sq} is the synchronous q-axis reactance

θ_0 is the initial angle between the axis of phase A and the rotor d-axisqaxis reactance

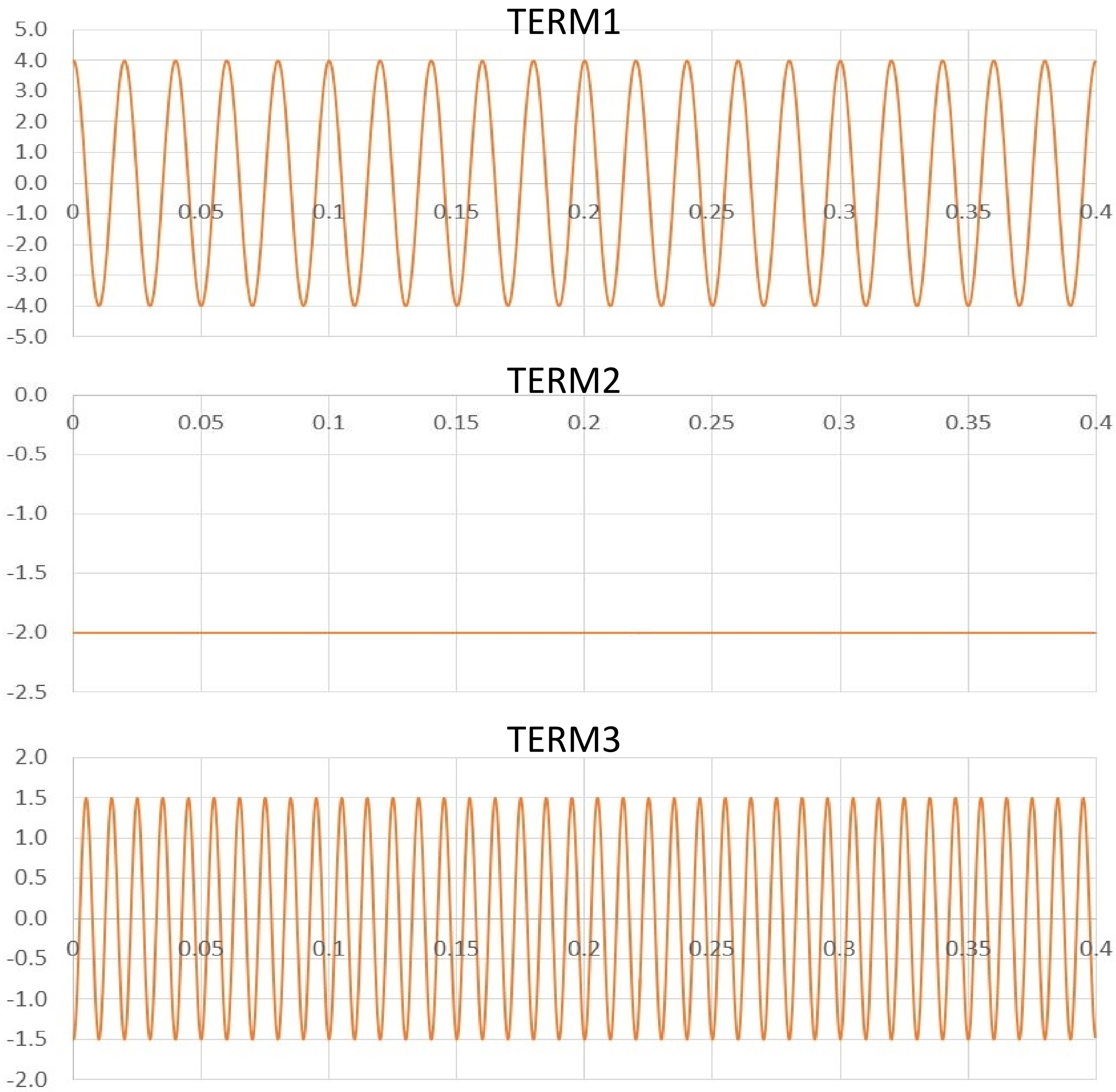
And similarly for i_b and i_c with due account of the fact that θ_0 is different in each phase:

Some observations on the above

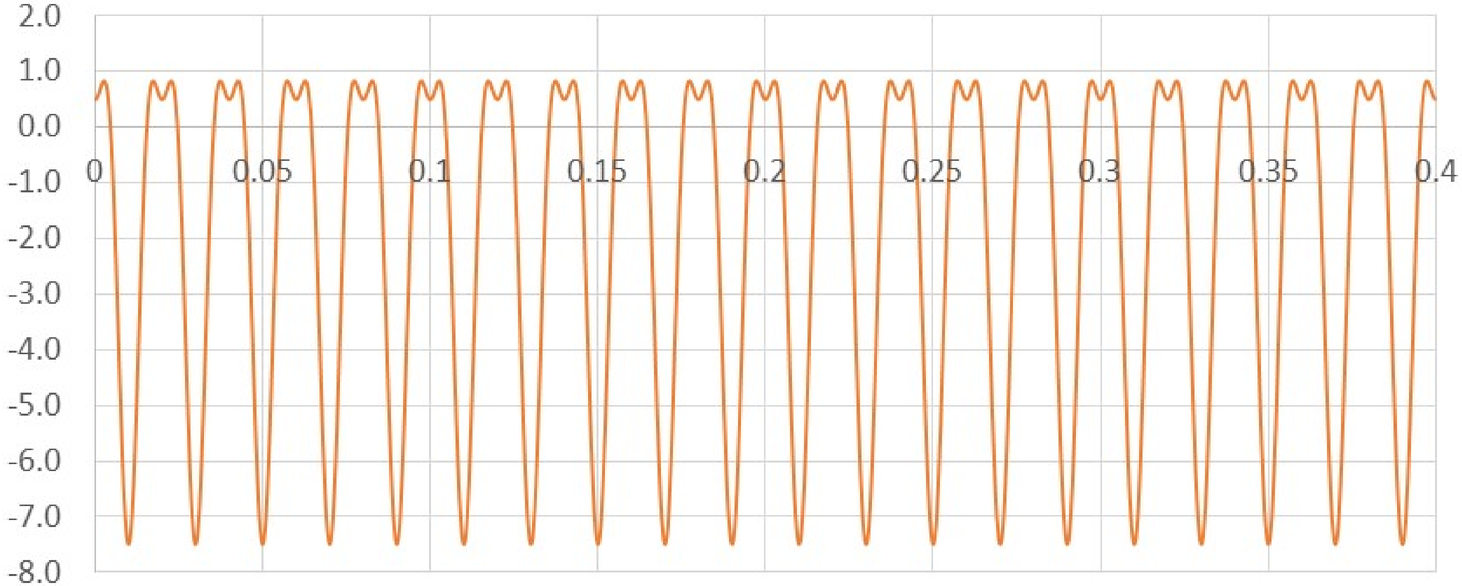
- The DC component is a function of θ_0, i.e. the instant on the cycle when the short-circuit occurs
- Since the 3-phase are phase shifted by 120°, then θ_0 cannot be the same for all phases – therefore there will be asymmetry in the DC component between the three phases

Consider an example in which:

F= 50Hz
x_d'=0.25 per unit
x_{sq} = 1.0 per unit
θ_0 = 0°



Net short-circuit current in phase A - undamped

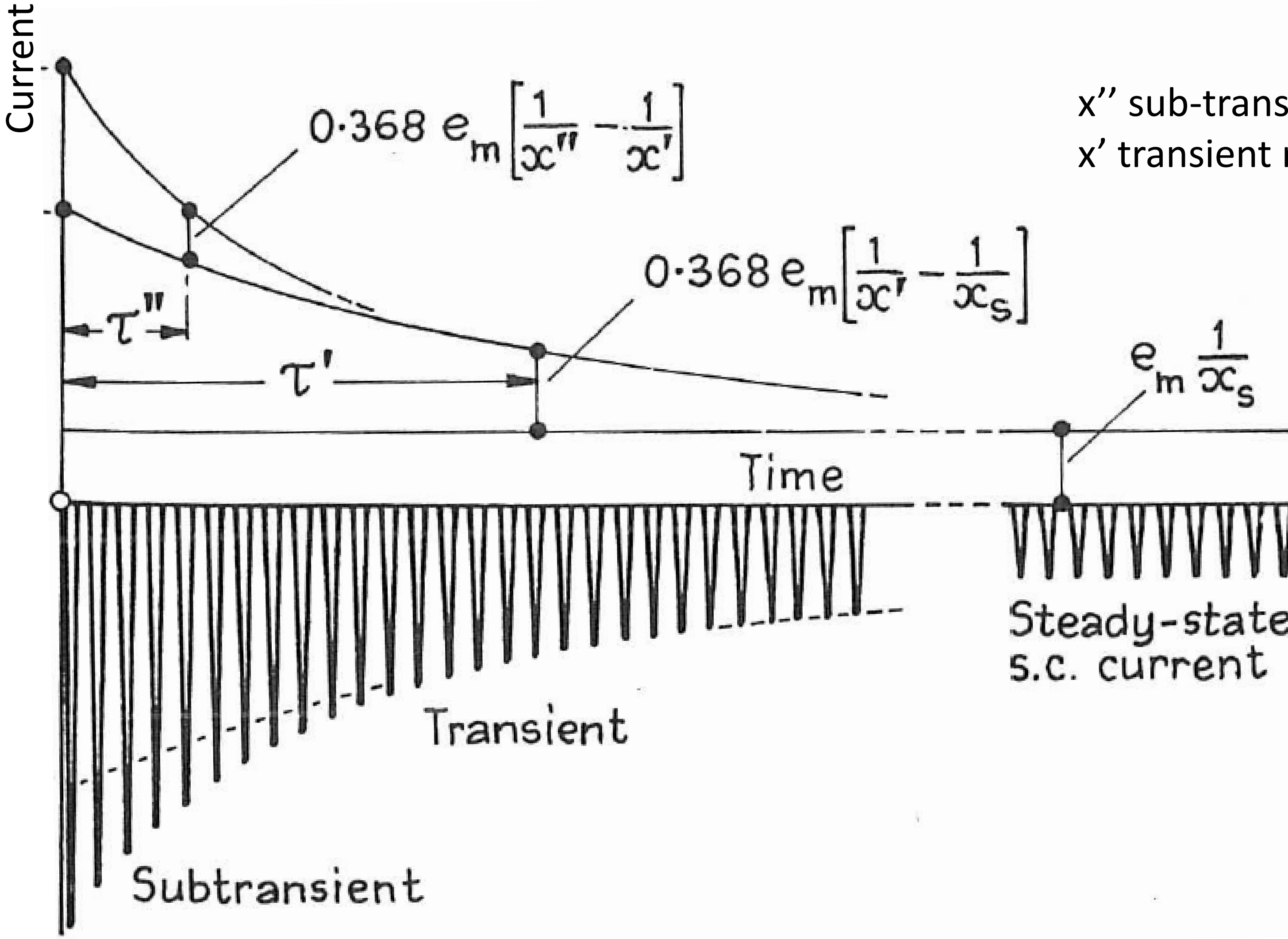


In practice, there is always damping of this behaviour due to the presence of resistance and eddy current losses

However, there are different damping behaviours exhibited for the various components, i.e. it is not a simple L/R type decay envelope on the waveform

Predicting the various decays requires the use of so-called sub-transient reactance (x'')

x’’ sub-transient reactance
x’ transient reactance



The solution of the currents in each phase is substantially more complicated when the effects of resistance are added in (See B. Adkins ‘The general theory of electrical machines’, Chapman Hall)

Taking as an example, the current in phase A on a machine which is initially excited but unloaded is:

$$i_a = v_q \left[\frac{1}{x_{sd}} \cos(\omega_1 t + \theta_0) \right.$$	steady-state s.c. component
$$+ \left(\frac{1}{x_d'} - \frac{1}{x_d} \right) \exp\left(-\frac{t}{\tau_d'} \right) \cos(\omega_1 t + \theta_0)$$	normal-freq. transient
$$+ \left(\frac{1}{x_d''} - \frac{1}{x_d'} \right) \exp\left(-\frac{t}{\tau_d''} \right) \cos(\omega_1 t + \theta_0)$$	normal-freq. subtransient
$$- \frac{x_d'' - x_q''}{2 x_d'' x_q''} \exp\left(-\frac{t}{\tau_a} \right) \cos(2\omega_1 t + \theta_0)$$	double-freq. transient
$$\left. - \frac{x_d'' + x_q''}{2 x_d'' x_q''} \exp\left(-\frac{t}{\tau_a} \right) \cos \theta_0 \right]$$	asymmetric (d.c.) transient

Loaded and asymmetric conditions involve additional complexity!

The various reactances and time constants are:

Reactances	
Synchronous: d-axis	$x_{sd} = x_{ad} + x$
q-axis	$x_{sq} = x_{aq} + x$
Transient: d-axis	$x_d' = \frac{x_{ad} x_f}{x_{ad} + x_f} + x$
Subtransient: d-axis	$x_d'' = \frac{x_{ad} x_f x_{kd}}{x_{ad} x_f + x_f x_{kd} + x_{kd} x_{ad}} + x$
q-axis	$x_q'' = \frac{x_{aq} x_{kq}}{x_{aq} + x_{kq}} + x$

Time-constants	
O.C. transient: d-axis	$\tau_{d0}' = \frac{1}{\omega_1 r_f} [x_{ad} + x_f]$
O.C. subtransient: d-axis	$\tau_{d0}'' = \frac{1}{\omega_1 r_{kd}} \left[\frac{x_{ad} x_f}{x_{ad} + x_f} + x_{kd} \right]$
q-axis	$\tau_q'' = \frac{1}{\omega_1 r_{kq}} [x_{aq} + x_{kq}]$
S.C. transient: d-axis	$\tau_d' = \frac{1}{\omega_1 r_f} \left[\frac{x_{ad} x}{x_{ad} + x} + x_f \right]$
S.C. subtransient: d-axis	$\tau_d'' = \frac{1}{\omega_1 r_{kd}} \left[\frac{x_{ad} x_f x}{x_{ad} x_f + x_f x + x_{ad} x} + x_{kd} \right]$
q-axis	$\tau_q'' = \frac{1}{\omega_1 r_{kq}} \left[\frac{x_{aq} x}{x_{aq} + x} + x_{kq} \right]$
S.C. armature (d.c.)	$\tau_a = \frac{1}{\omega_1 r} \left[\frac{2 x_d'' x_q''}{x_d'' + x_q''} \right]$

Typical per unit values for a non-salient turbo-generator are:

Component	Per unit
Synchronous reactance (x_{sd} and x_{sq})	1.0-2.5
Armature leakage reactance (x)	0.1-0.25
Sub transient reactance (x_d'' and x_q'')	0.1-0.25
Transient ($x_d'$and x_q')	0.2-0.35
DC component time constant (τ_a)	0.1-0.2
Sub-transient (τ'')	0.03-0.1
Transient (τ')	1-1.5