ELEC0014 - Introduction to power and energy systems

Introduction to balanced fault analysis

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Fault [1]: another name for *short-circuit*

Causes :

- lightning on overhead lines: by far the most frequent
- snow, ice, etc. accumulating on conductors
- trees or other objects touching the phases
  due to storm or human mistakes (f.i. civil engineering vehicles)
- internal failure of a component (in switching stations)

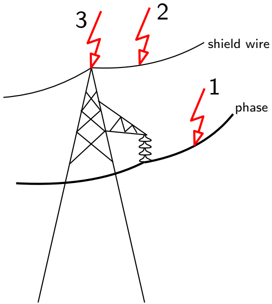
An essential part of the design of a power system is the calculation of currents flowing under the effect of faults. Also needed after system evolutions.

The computed fault currents and other quantities (such as the impedances seen from the extremities of lines) are used to :

- choose the settings of protections
- choose the ratings of the circuit breakers.

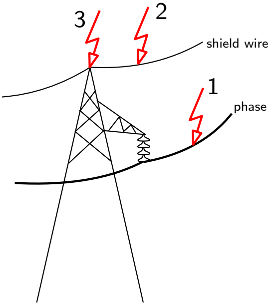
[1] en français: défaut

How lightning can result in a short-circuit



1 : lightning stroke on a phase conductor (protection by shield wire failed)

- Electric charges injected in both directions
- causing two high-voltage waves to travel along the conductor ($Z_c I_{lightning}/2 \simeq 300 \times 30.000/2 = 4\ 500\ 000$ V !)
- nearest insulator strings subjected to a very high voltage difference
- dielectric breakdown of air interval (between arcing horns)
- high-voltage wave propagation stopped (does not reach substations)
- but electric arc between the phase and the tower (connected to earth).



2 : lightning stroke on the shield wire
3 : lightning stroke on a tower

- Very large current flowing into the metallic tower and the ground resistance
- causing a voltage rise of the upper part of the tower
- high voltage difference appears between the point of connection of the insulator string and the phase conductor
- dielectric breakdown of air interval (between arcing horns)
- electric arc between the phase and the tower (connected to earth).

Even after the lightning charges have dispersed into Earth. . .

- the ionized air has lost its insulation properties
- an electric arc remains, in which the current is now fed by the (nearby) generators !

Short-circuits must be promptly cleared :

- short-circuit currents $\gg$ currents admissible in steady state
  $\Rightarrow$ equipment can be damaged
- they can cause system instability
  (loss of synchronism between generators or voltage instability)
- voltage drop is a nuisance for consumers electrically close to the fault. Electronic appliances, motors, industrial processes, etc. are sensitive to *voltage sags*.

Protections and circuit breakers

Fault clearing by protections and circuit breakers :

- the protections at the end of the line detect the fault
- the circuit breakers at both ends open
- the electric arc is no longer fed and extinguishes
- the transmission line is out of service.

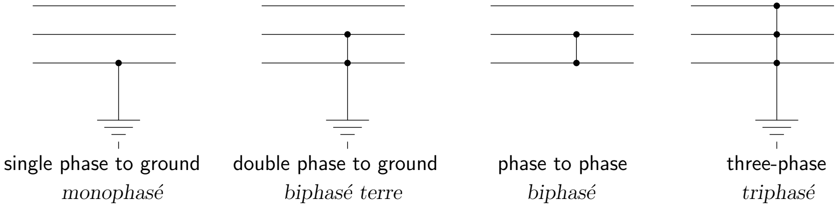
Typical fault clearing times :

- transmission networks:
  - at most 5 cycles (0.1 s at 50 Hz)
  - some high-speed circuit breakers can operate in 2 cycles
- sub-transmission and distribution networks: 8 cycles or more
  - impact of longer clearing less important at lower voltage levels.

At transmission level, it is usual to have an *auto-reclosure* scheme:

- to restore the pre-fault network topology
- requires waiting for the air to recover its insulation properties $\rightarrow$ delay $\simeq 0.3$ s
- if the fault is permanent (object touching the line and not already burnt by the short-circuit current): new tripping of the line, and locking.

Types of faults



Single phase to ground faults :

- the most frequent.
  Example: Belgian 400-kV grid : 91 % of faults (2006-2014)

Three-phase faults :

- much less frequent. Example: Belgian 400-kV grid : only 2 % of faults
- but the most severe
- considered as a worst case that the network must be able to withstand.

This chapter focuses on three-phase faults with the same (in particular zero) resistance between each phase and the ground

- the network remains electrically balanced → *balanced fault analysis*
- per-phase analysis can still be used.

Behaviour of the synchronous machine during a three-phase fault

Over a time interval of $\simeq 0.1 - 0.2$ s after a short-circuit occurrence:

- generator rotor speed cannot change significantly (inertia)
- transients are of electromagnetic nature : variations of magnetic flux linkages in machine windings.

Study of a simple case:

- round-rotor generator with synchronous reactance X and stator resistance R_a
- operating initially with stator open
- subject at $t = 0$ to a "solid" [2] three-phase short-circuit
- with constant field voltage : $v_f = R_f i_f^o$ (i_f^o: pre-fault field current)
- with constant speed, equal to nominal value. Hence : $\theta_r = \theta_r^o + \omega_N t$

Thus, the pre-fault voltage magnitude is : $V(0^-) = E_q^o = \frac{\omega_N L_{af}}{\sqrt{2}} i_f^o$

[2] this means "without impedance". En français : défaut "franc"

Analytical expression of current in phase a during the short-circuit

$$i_a(t) = -\sqrt{2}E_q^o \left[\frac{1}{X} + \left(\frac{1}{X'} - \frac{1}{X} \right) e^{-t/T_d'} + \left(\frac{1}{X''} - \frac{1}{X'} \right) e^{-t/T_d''} \right] \cos(\omega_N t + \theta_r^o)$$
$$+\sqrt{2}E_q^o \frac{1}{X''} e^{-t/T_\alpha} \cos\theta_r^o$$

- Oscillatory component with RMS value starting at $\frac{E_q^o}{X''}$ and tending to $\frac{E_q^o}{X}$;
- aperiodic (or *unidirectional* or *direct*) component, tending to zero.

$$\lim_{t=0} i_a(t) = 0 \qquad \text{for } t \text{ large enough : } i_a(t) \simeq -\sqrt{2}\frac{E_q^o}{X}\cos(\omega_N t + \theta_r^o)$$

X''	subtransient reactance	0.15 - 0.30 pu
X'	transient reactance	0.20 - 0.40 pu
T_d''	subtransient short-circuit time constant	0.02 - 0.05 s
T_d'	transient short-circuit time constant	0.5 - 2.0 s
$T_\alpha \simeq X''/(\omega_N R_a)$	aperiodic time constant	0.02 - 0.35 s

(values in per unit on the machine base)

Numerical example

Data:

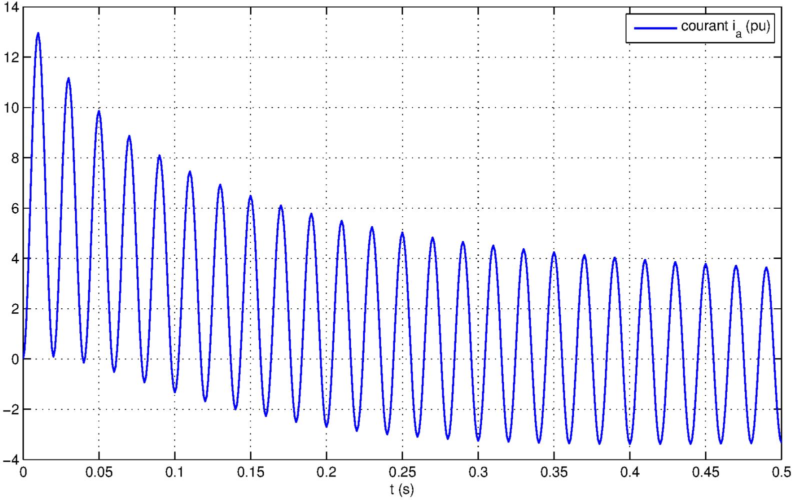
$$X = 2 \text{ pu} \qquad X^{'} = 0.3 \text{ pu} \qquad X^{''} = 0.2 \text{ pu} \qquad R_a = 0.005 \text{ pu}$$

$$T_d^{''} = 0.0333 \text{ s} \qquad T_d^{'} = 1.35 \text{ s} \qquad T_\alpha = \frac{X^{''}}{2\pi 50 R_a} = 0.127 \quad \text{s}$$

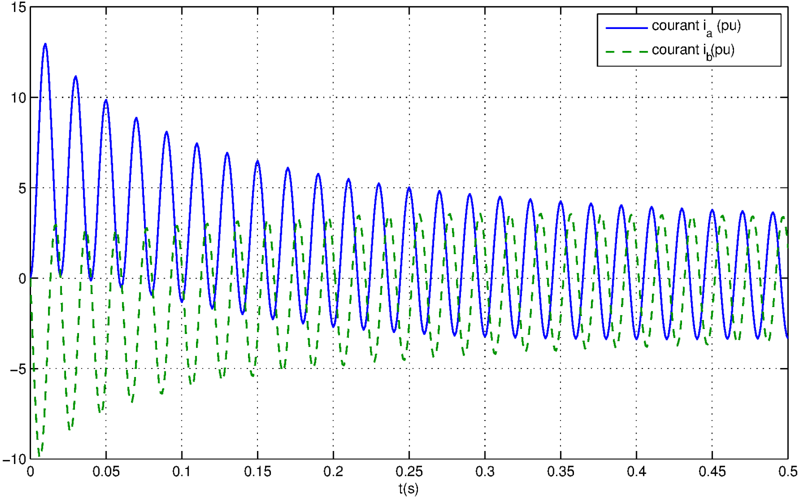
We assume:

- $E_q^o = 1 \quad \text{pu}$
- $\theta_r^o = 0$: the short-circuit takes place at the moment the direct axis of the rotor coincides with the axis of phase *a*;
  "worst case" for the direct current component, which is maximum in phase *a*.

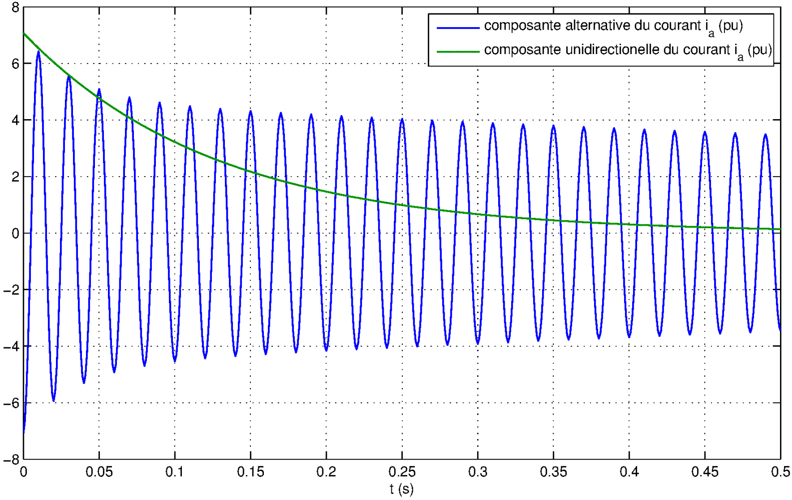
Current in phase a over a time interval $\simeq 15\,T_d^{''} \simeq \frac{T_d^{'}}{3}$



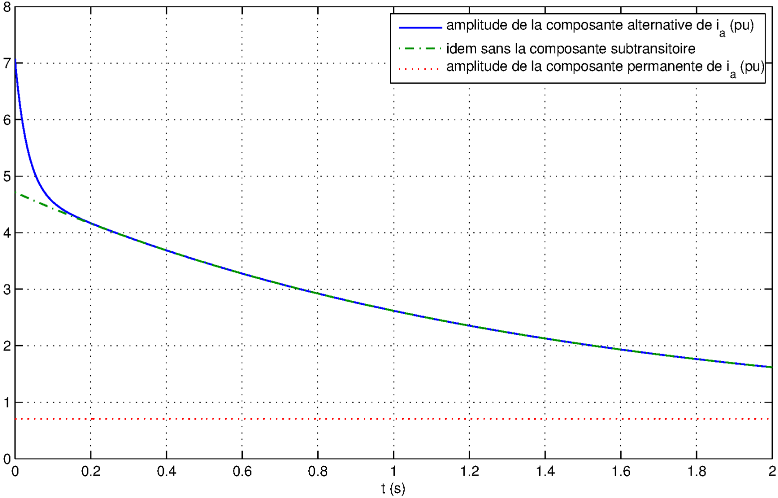
Currents in phases *a* and *b*



Alternating and aperiodic components of current i_a

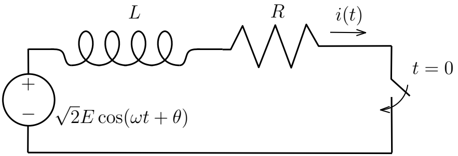


Amplitude of the alternating component of current i_a



The amplitude of the current that the circuit breaker has to interrupt is significantly larger than the current that would prevail in steady state !

Explanation of current evolution



Analogy :
short-circuit of an AC source in series with an (R,L) circuit

$$\phi = atan\left(\frac{\omega L}{R}\right)$$

$$i(t) = -\left[\frac{\sqrt{2}E}{\sqrt{R^2+\omega^2 L^2}}\cos(\theta-\phi)\right]e^{-\frac{R}{L}t} + \frac{\sqrt{2}E}{\sqrt{R^2+\omega^2 L^2}}\cos(\omega t+\theta-\phi)$$

- First term similar to the aperiodic component of the short-circuit current
- but the amplitude of the oscillatory component is constant.

In the short-circuited synchronous machine :

- fault → stator AC currents → rotating magnetic field
- flux linkage in field winding cannot change quickly (long time constant T'_d)
- additional i_f component induced to maintain constant flux linkage
- E_q (proportional to i_f) increases[3] → larger current in the stator windings
- similar reaction of damper windings, but with shorter time constant T''_d.

[3] unlike in the above circuit, where E is constant

Usual simplifications for the computation of fault currents

- Aperiodic components of the short-circuit currents are neglected
  - their amplitudes are not the same in the three phases
  - their amplitudes depend on the time of the fault occurrence
  - this can be compensated by multiplying the fault current by

    1.4 if the breaker opens in 2 cycles
    1.2 if it opens in 3 cycles
    1.0 if it opens in 8 cycles
- only the alternating components at frequency ω_N are considered.
  $\Rightarrow$ circuit analysis techniques of sinusoidal steady state can be used !

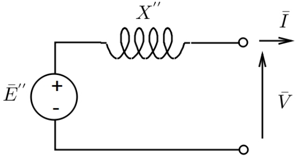
Which reactance consider ?

- faults in transmission networks:
  for security, it is considered that circuit breakers must be able to interrupt the *initial* amplitude of the oscillatory component
  $\Rightarrow$ consider the subtransient reactance X'' of synchronous machines
- faults in distribution networks: circuit breakers take more time to open
  $\Rightarrow$ consider the transient reactance X' of synchronous machines.

Equivalent circuit of a synch. machine in s-c calculations

The equivalent circuit with E_q behind the synchronous reactance is not convenient since E_q changes abruptly following the short-circuit.

The following circuit is more appropriate :



$\bar{E}''$: *emf behind subtransient reactance* :

- is shown to be proportional to flux linkages in rotor windings
- remains constant during the short-circuit, unlike E_q.

Owing to its continuity before and after short-circuit, the emf $\bar{E}''$ is determined from the pre-fault operating conditions (denoted with 0^-):

$$\bar{E}''(0^+) = \bar{E}''(0^-) = \bar{V}_a(0^-) + jX_d''\bar{I}(0^-)$$

Similarly for the emf $\bar{E}'$ behind transient reactance X', if the latter is to be used.