ELG4125: Symmetrical Faults

Transmission lines stretch over large distances and are subject to faults involving one or more phases and ground. Such faults cause momentary power outages but, more important, if a protective action is not taken, can cause permanent damage to transmission equipment such as the transmission line itself and/or the transformer.

Faults

- A **fault** in a circuit is any failure that interferes with the normal flow of current to the load.
- In most faults, a short circuit path forms between two or more phases, or between one or more phases and the neutral (ground).
- Since the impedance of a new path is usually low, an excessive current may flow.
- High-voltage transmission lines have strings of **insulators** supporting each phase. The insulators must be large enough to prevent **flashover**–a condition when the voltage difference between the line and the ground is large enough to ionize the air around insulators and thus provide a current path between a phase and a tower.

Causes of Faults

- Tree Branches near the right-of-way on transmission lines and shorting them to ground.
- Lightning that represents a current source of thousands of amperes. This current flowing through the tower footing impedance can raise the tower potential above the local ground to such a level that without surge arresters, the insulator strings may flash over.
- The reason to analyze faults are
  - To set the relays so that can detect it.
  - To make sure that the circuit breakers ratings are such that they are capable of interrupting the fault currents.

Transmission Fault Types

- There are two main types of faults:
  - **Symmetric faults:** system remains balanced; these faults are relatively rare, but are the easiest to analyze so we'll consider them first.
  - **Unsymmetric faults:** system is no longer balanced; very common, but more difficult to analyze.
- The most common types of faults on a three phase system are:
  - Single line-to-ground (SLG)
  - Line-to-line faults (LL)
  - Double line-to-ground (DLG) faults
  - Balanced three phase faults.

- If flashover occurs on a single phase of the line, an arc will be produced. Such faults are called single **line-to-ground faults**.
- Since the short-circuit path has a low impedance, very high currents flow through the faulted line into the ground and back into the power system.
- Faults involving ionized current paths are also called transient faults. They usually clear if power is removed from the line for a short time and then restored.
- Single line-to-ground faults can also occur if one phase of the line breaks comes into contact with the ground or if insulators break. This fault is called a permanent fault since it will remain after a quick power removing.
- Approximately 75% of all faults in power systems are either **transient** or **permanent single line-to-ground faults**.

Type of fault	Abbreviation	Type
Single line-to-ground	SLG	Unsymmetrical
Line-to-line	LL	Unsymmetrical
Double line-to-ground	LLG	Unsymmetrical
Symmetrical three-phase	3P	Symmetrical

- **Sometimes**, all three phases of a transmission line are shorted together; this is called **symmetrical three-phase faults**.
- **Two phases** of a line may touch, or flashover may occur between two phases; this is called a **line-to-line fault**.
- When two lines touch each other and also touch the ground, the fault is called a **double line-to-ground fault**.
- **Lighting strokes** cause most faults on high-voltage transmission lines producing a very high transient that greatly exceeds the rated voltage of the line. This voltage usually causes flashover between the phase and the ground of the line creating an arc. Once the current starts flowing through the arc, it remains even after the lighting disappears.

Lightning Strike Event Sequence

1. Lighting hits lines, setting up an ionized path to the ground
   - Millions lightning strikes per year hits every year!
   - A single typical stroke might have 25,000 amps, with a rise time of 10 μs, dissipated in 200 μs.
   - Multiple strokes can occur in a single flash, causing the lightning to appear to flicker, with the total event lasting up to a second.
2. Conduction path is maintained by ionized air after lightning stroke energy has dissipated, resulting in high fault currents (often > 25,000 amps)
3. Within one to two cycles (16 ms) relays at both ends of line detect high currents, signaling circuit breakers to open the line:
   - Nearby locations see decreased voltages
4. Circuit breakers open to de-energize line in a one to two cycles:
   - Breaking tens of thousands of amps of fault current is no small feat.
   - With line removed voltages usually return to near normal.
5. Circuit breakers may reclose after several seconds, trying to restore faulted line to service.

Fault Analysis

- Fault currents cause equipment damage due to both thermal and mechanical processes.
- The main goal of fault analysis is to determine the magnitudes of the currents present during the fault:
  - We need to determine the maximum current to ensure devices can survive the fault.
  - We need to determine the maximum current the circuit breakers (CBs) need to interrupt to correctly size the CBs.

To understand fault analysis we need to review the behavior of an *RL* circuit with a switch: transient response and steady state: Circuit Analysis.

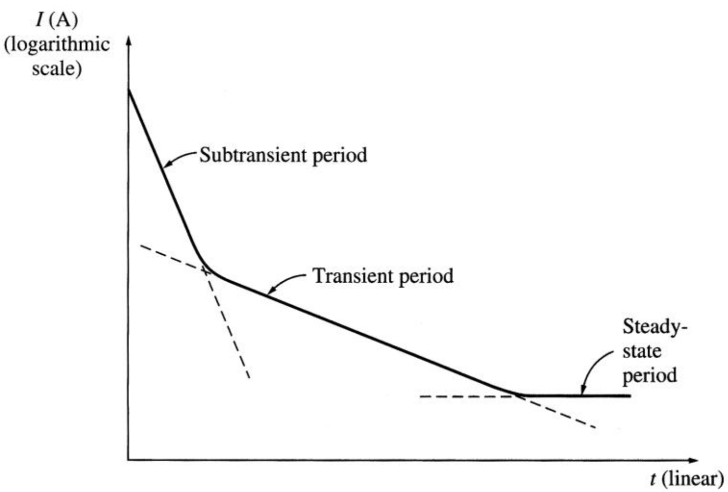
Network Fault Analysis Simplifications

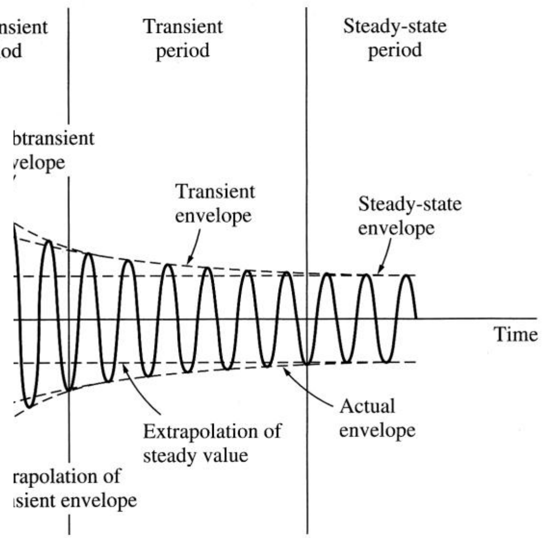
To simplify the analysis of fault currents in networks we will make several simplifications:

1. Transmission lines are represented by their series reactance
2. Transformers are represented by their leakage reactances.
3. Synchronous machines are modeled as a constant voltage behind direct-axis sub-transient reactance.
4. Induction motors are ignored or treated as synchronous machines
5. Other (non-spinning) loads are ignored.

Symmetrical AC Components of the Transient

Sub-transient: first cycle or so after the fault – AC current is very large and falls rapidly; **Transient:** current falls at a slower rate; **Steady-state:** current gets back to normal.





- The AC current flowing in the generator during the sub-transient period is called the sub-transient current and is denoted by I''. This current is caused by the damper windings of synchronous machines. The time constant of the sub-transient current is denoted by T'' and it can be determined from the slope. This current may be 10 times the steady-state fault current.
- The AC current flowing in the generator during the transient period is called the transient current and is denoted by I'. It is caused by a transient DC component of current induced in the field circuit of a synchronous generator at the time of fault. This transient field current increases the internal generated voltage of a machine and, therefore, an increased fault current.
- The time constant of a field circuit T' is much larger than the time constant of the damper winding, therefore, the transient period lasts longer than the sub-transient. This current is often as much as 5 times the steady-state fault current.

After the transient period, the fault current reaches a steady-state condition. the steady-state rms current is denoted by I_{ss} and is approximated by the fundamental frequency component of the internal generated voltage normalized by the synchronous reactance:

$$I_{ss} = \frac{E_A}{X_s}$$

The rms magnitude of the AC fault current in a synchronous generator varies over time as

$$I(t) = (I'' - I')e^{-t/T''} + (I' - I_{ss})e^{-t/T'} + I_{ss}$$

The sub-transient reactance is the ratio of the fundamental component of the internal generated voltage to the sub-transient component of current at the beginning of the fault:

$$X'' = \frac{E_A}{I''}$$

Similarly, the transient reactance is the ratio of the fundamental component of the internal generated voltage to the transient component of current at the beginning of the fault. This value of current is found by extrapolating the transient region back to time zero

$$X' = \frac{E_A}{I'} \qquad I'' = \frac{E_A}{X''} \qquad I' = \frac{E_A}{X'}$$

Example 1: A 100 MVA, 13.8 kV, Y-connected, 3 phase 60 Hz synchronous generator is operating at the rated voltage and no load when a 3 phase fault occurs at its terminals. Its reactances per unit to the machine's own base are

$$X_s = 1.00 \qquad X' = 0.25 \qquad X'' = 0.12$$

and the time constants are

$$T' = 1.10\, s \qquad T'' = 0.04\, s$$

The initial DC component in this machine averages 50 percent of the initial AC component.

- What is the AC component of current in this generator the instant after the fault?
- What is the total current (AC + DC) in the generator right after the fault occurs?
- What will the AC component of the current be after 2 cycles? After 5 s?

The base current of the generator can be computed as

$$I_{L,base} = \frac{S_{base}}{\sqrt{3}V_{L,base}} = \frac{100,000,000}{\sqrt{3}\cdot 13,800} = 4,184\ A$$

The sub-transient, transient, and steady-state currents are (per-unit and Amps)

$$I'' = \frac{E_A}{X''} = \frac{1.0}{0.12} = 8.333\ pu = 34,900\ A$$

$$I' = \frac{E_A}{X'} = \frac{1.0}{0.25} = 4\ pu = 16,700\ A$$

$$I_{ss} = \frac{E_A}{X_s} = \frac{1.0}{1.0} = 1\ pu = 4,184\ A$$

a) The initial AC component of current is *I"* = 34,900 A.

b) The total current (AC and DC) at the beginning of the fault is

$$I_{tot} = 1.5I'' = 52,350\ A$$

c) The AC component of current as a function of time is

$$I(t) = (I'' - I')e^{-\frac{t}{T''}} + (I' - I_{ss})e^{-\frac{t}{T'}} + I_{ss} = 18,200 \cdot e^{-\frac{t}{0.04}} + 12,516 \cdot e^{-\frac{t}{1.1}} + 4,184\ A$$

After 2 cycles t = 1/30 s and the total current is

$$I\left(\frac{1}{30}\right) = 7,910 + 12,142 + 4,184 = 24,236\ A$$

which has the largest contribution from the transient current component – transient period. At 5 s, the current reduces to

$$I(5) = 0 + 133 + 4,184 = 4,317\ A$$

which is in a steady-state period.