

Module 2 : Equipment and Stability Constraints in System Operation

Lecture 6 : Transmission Line constraints

Objectives

In this lecture you will learn the following

- Thermal and dielectric limitations of a transmission line.
- Effect of loading on voltages, for long distance ac transmission.
- AC line loadability (power transmission capability) versus distance.

Transmission line thermal limits

A large current flow increases the losses in the form of heat. This results in increased conductor temperatures. Excessive temperature may result in expansion and resultant sag of conductors causing decreased clearance to ground. Temperature extremes have an "annealing effect" causing reduced mechanical strength of aluminum.

Since thermal time constants are large, it is useful to distinguish between steady state and transient thermal ratings.

Thermal Capability is a function of 1) ambient temperature 2) Wind conditions 3) Condition of conductor 4) Conductor type and 5) ground clearance.

Typical *steady state* thermal specifications of conductors used for 400 kV overhead transmission:

ACSR (aluminum conductor steel reinforced) *Moose* Conductor (520 sq mm): For an ambient temperature of 40° C, and a maximum conductor temperature of 75° C, ampacity is 700 A (approx.). Typically, two moose conductors form a bundle of 400 kV line so that the total ampacity is 1400A for such a line.

If **AAAC (all aluminum alloy conductor) of 520 sq mm** is used, higher conductor temperatures as compared to ACSR are possible. For an ambient temperature of 40° C, and a maximum conductor temperature of 85° C, ampacity is 850 A (approx.).

The thermal ratings are a strong function of **ambient conditions** (wind flows, solar radiation) and absorption and emissivity of the conductor material ; it makes sense to evaluate the actual ampacity during real time operation (season to season, day to day or hour to hour).

Dielectric Limits

Exceeding dielectric limits (maximum electric field strength) results in failure of insulation, causing faults. See a photograph of dielectric breakdown in an insulator [here](#). Electric fields may be excessive (due to overvoltage) under low loading conditions on long ac transmission lines (Ferranti Effect) or during abnormal conditions like lightning strokes.

Deviation of voltages beyond certain limits can also be considered to be an unacceptable compromise on the quality of power being supplied to consumers. Low or high voltages can also damage electrical equipments.

Voltages and reactive power demand of transmission lines are affected by:

- Line parameters
- Length of line
- Power transfer

Given a nominal voltage rating, a steady state overvoltage of about 10% is often permissible. Shunt reactors (inductors) are often connected in shunt on transmission lines to prevent overvoltages under low loading. If permanently connected to a line, however, they may excessively reduce the voltages during heavy load conditions.

Line Parameters: Line parameters are dependent on the conductor dimensions and relative placement. The surge impedance of most overhead lines is around 250-350 ohms whereas it is 30-50 ohms for cables.

Typical *positive sequence* inductance and capacitance parameters for a 400 kV overhead line: $L = 1.044 \text{ mH/km}$, $C = 12 \text{ nF/km}$. For EHV lines, X/R ratio is large. The resistance per unit length of this line = 0.0296 ohm / km

For a 400 kV paper-insulated lead-covered(PILC) cable, typical *positive sequence* parameters are:

$L = 0.78 \text{ mH/km}$, $C = 0.95 \text{ uF/km}$.

Note the high capacitance as compared to an overhead line.

What is the **Surge Impedance Loading (SIL)** of the overhead line and cable?

To analyse the effect of various parameters, we now have a quick look at the basic [equations of a lossless transmission line](#).

How does voltage vary in an AC transmission Line?

Important results for lossless lines (EHV lines have low resistance, so lossless line approximation is valid).

Voltage profile along the line is flat only if $R = Z_c$ is connected at receiving end (SIL). Under this situation, there is no demand of reactive power from either sending or receiving ends. Loads are decided by consumers and not by a system operator. As such, this exact condition is practically never met although it is ideal.

If voltage at both ends is maintained at 1.0 pu (say, by controlling excitation of generators connected at both ends), the voltage tends to sag as we move towards the midpoint if $P_s > \text{SIL}$. The line absorbs reactive power.

If $P_s < \text{SIL}$, voltage swells and the line generates reactive power.

For a line which has one end maintained at 1.0 pu but kept open-circuited at the other end, overvoltage will be evident at the open end.

All these effects are very prominent for long lines.

Cables have very high SIL (why?). The current at SIL usually exceeds the thermal rating of a cable. Therefore a cable is invariably loaded below its SIL. Cables, therefore, generate reactive power and usually voltages can be very high at low loading levels, especially for long lengths. Besides this, cables are much costlier than overhead lines and are more "unforgiving" towards overloads. Therefore, cables of lengths exceeding 30-40km are rarely used for ac transmission.

Due to voltage problems (and stability problems, which we shall study in the following lecture), underwater cable transmission and bulk transfer over very long distances is carried out using DC transmission technology. We shall study the essentials of this technology later in the course.

We now will illustrate voltage variation in a long transmission line by an [example](#).

Line Loadability in AC lines

In order to prevent overvoltages at light loads, it is necessary to have devices for absorbing reactive power (like

shunt reactors) not only at either end of a long line but even at intermediate points. Generators connected at the ends of the line have limited reactive power absorption capability as defined by their capability curves. If transmission redundancy exists (i.e., parallel transmission paths exist), then a very lightly loaded long line may be tripped to avoid overvoltage. However this may be detrimental to system security if some additional line trippings take place due to faults. If shunt reactors are permanently connected, they result in large sags in the voltage under heavy loading conditions. Moreover, reactive power demanded by long transmission lines under these situations may be excessive and may lead to system-wide low voltage conditions.

Compensation of a line involves changing the effective line parameters by connecting (lumped) capacitors in series and shunt. These compensating elements effectively reduce the line reactance and increase the shunt susceptance, thereby decreasing the surge impedance. Thus the effective SIL of a capacitor compensated line is higher than an uncompensated line. This increases the loadability of a long line.

Since total conductor cross-sectional area for EHV lines is mainly decided by electric field considerations (corona), these lines have large thermal capabilities, much in excess of the SIL. For long EHV lines, one cannot deviate much from SIL due to voltage constraints. Therefore, the thermal limit of a long EHV line is *not* the key limiting factor. However, thermal limit is the main limiting factor for short lines (< 100 km) wherein voltage constraints are not violated even for large deviations from SIL.

The line loadability as a function of distance can be obtained by considering thermal and voltage limits as given in this [example](#).

Additional limits are imposed by stability and are discussed in the next lecture.

Recap

In this lecture you have learnt the following

- Power transfer capability of a ac line is restricted by thermal and voltage constraints
- Short lines are limited by thermal constraints
- Long lines are limited by voltage constraints. Stability constraints are also important for long ac lines and are studied in the next lecture
- Congratulations, you have finished Lecture 6. To view the next lecture select it from the left hand side menu of the page.