



# Flexible Alternating Current Transmission Systems (FACTS), Volume I

An Online Continuing Education Course for Engineers

**Course Number: E-4079**

**Credit: 4 Hours / 4 PDH / 4 CPD**

# Flexible Alternating Current Transmission Systems (FACTS), Volume I

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## Introduction

The electric supply system in the United States is comprised of a complex network of generators, transmission lines, transformers, and other components, all of which are designed to serve a variety of loads. The supply system is highly interconnected for economic reasons. The interconnected systems benefit by exploiting load diversity, sharing of generation reserves, and the economy gained from the use of large generating units. There is a downside to the integrated power system - the security can be adversely affected such as when disturbances initiated in a particular area spread and propagate over the entire system; it results in major blackouts caused by cascading outages.

Electrical energy is transported from the generating point to the point of use through interconnected transmission lines. Figure 1 is a view of the interconnected electric system in the U.S.

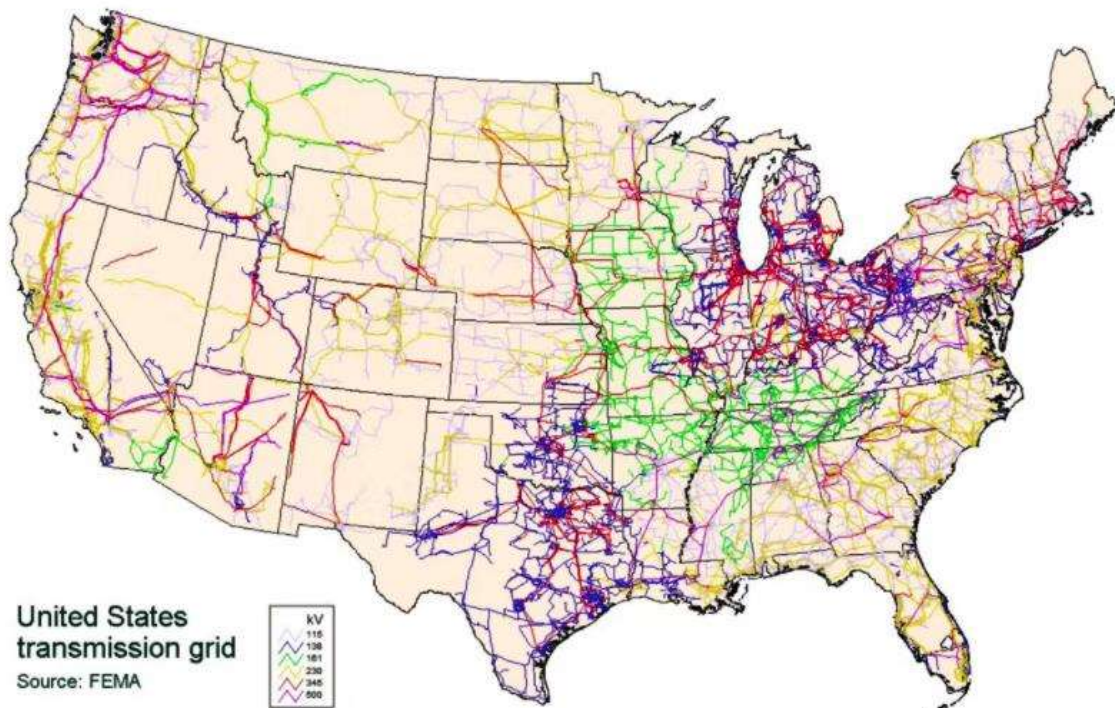


Figure 1

The flow of electricity follows the path of least impedance, and this natural flow of electricity may cause certain transmission lines to be overloaded or underloaded. The industry has devices to provide some control over the power flow, but these devices are slow, cumbersome, and do not always react promptly.

In recent years, the electric system has come under strain as electric demand grows and new types of generation are added to the system, some of which are very remote from the load centers. Further exacerbating the strain on the electric system is the public's opposition to the construction of new transmission line corridors. As a consequence of growing power demand, some transmission lines are becoming more loaded than initially planned and this increased loading of long transmission lines creates transient stability issues. Transient stability refers to the capability of a system to maintain synchronous operation in the event of large disturbances such as short-circuit faults. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship.

Mechanically controlled circuit breakers handle most switching and control of the electric power system. Unfortunately, the long operating times and discrete operation make it difficult for these devices to handle the frequently changing loads smoothly and to damp out the transient oscillations quickly. The utility industry compensates for these drawbacks by using large operational margins and redundancies to protect the system from dynamic variation and to recover from faults. This reduces the efficiency of the power system and increases the complexity of maintaining acceptable system reliability.

The power flow in a transmission line can vary even under normal steady-state conditions. For instance, the tripping of a generator or a transmission line can result in a sudden increase or decrease in power flow. This may result in the overloading of some transmission lines which creates a threat to system security. The system may be subjected to transient instability and cascading outages as individual generators and transmission lines trip due to the action of protective relays. If the system is operating close to the stability region, even a small disturbance can lead to large power swings and blackouts.

An increased transmission line loading can lead to voltage collapse due to the shortage of reactive power delivered at the load centers. This is due to the increased consumption of the reactive power in the transmission network and the characteristics of the load. The utility industry manages this problem by ensuring sufficient power transfer margins are maintained.

Providing large operating margins reduces the efficient transfer of power. These stability margins can be substantially reduced with the use of high-power electronic controllers for fast dynamic control over reactive and active power.

## Increasing Transmission Capacity

It is possible to enhance the existing transmission system infrastructure capacity. To achieve a structure for comparison, the grid parameter affected by each technology are broadly classified into three categories:

1. Increased power transfer
2. Improved voltage stability
3. Enhanced system frequency stability

As with any system, these three specified categories of grid parameters are not isolated. Targeted improvements to one grid parameter can have ancillary and indirect benefits on another parameter.

### Fundamentals of Power Transfer Limits

The following sections describe the technical aspects of electric power transfer.

#### Surge Impedance Loading

*Surge impedance loading* (SIL) of a power transmission line is the nominal power flow capacity based on the design characteristics of the line and its operating voltage. SIL is governed more by the overall geometry of the line and its operating voltage, and less by the conductor size. SIL is independent of the line length. SIL is not the maximum that a particular line can carry, but rather a benchmark that can be used to compare lines of different designs and voltage ratings. SIL is a useful concept to compare different transmission lines.

For a typical 500 kV overhead transmission line, the surge impedance is around 238 ohms. This results in a SIL of around 1,050 MW. This is based on the relationship,

$$\mathbf{SIL = \frac{V_{Line}^2}{X_{Line}} = \frac{500^2}{238} = 1,050 \text{ MW}}$$

Short lines may be able to carry twice the base SIL. Long lines of the same construction may be limited to less than 1,050 MW by system considerations.

Reactive loading and losses can become a limiting problem if a significant number of the lines are loaded above their SIL. As loading increases appreciably above SIL for many lines in the system, the reactive losses will increase to the square of the current and the line reactance. Adding high-capacity lines, instead of improving the power transfer capability of the system, could further increase the reactive losses and, consequently, further hamper power transfers.

## Thermal Limits

*Thermal limits* are the designed maximum flows that can be permitted through a transmission circuit, either continuously or for a short duration. The design parameters include the conductor type, conductor bundles, ambient temperature, wind speed, ice loading, and span length. The thermal limitation is critical in cases of lower voltage lines of 50 miles or less.

At extra-high voltages, environmental considerations, such as corona discharge and field effects, dictate line designs and usually result in higher thermal capabilities, which can exceed the realistic power transfer. For extra-high voltage transmission, line terminating equipment, such as wave traps and substations, impose a thermal limit rather than the line itself. Consequently, thermal limits are significant only for short lines at 138 kV and below.

## System Limits

*System limits* are functions of transmission line reactance in relation to the overall power system.

Series reactance, shunt admittance, and their combination can alter system transfer limits. This relationship must be considered when proposing changing the line surge impedance, either by adding equipment or by modifying the line itself. A transmission line's *series inductive reactance* is determined by conductor size, phase spacing, number of conductors, relative phasing, and line configuration. In long high-voltage overhead transmission lines, the series reactance is larger than the series resistance. For this reason, simple reconductoring of many long transmission lines, with no change to structure geometry, results in only minor changes in system power flows.

However, for shorter lines, the thermal capacity of the conductors or the characteristics of the system in which the line operates impose the power limits of that line. System limits can result from factors such as voltage drop, the possibility of voltage collapse, and system stability, both steady-state and transient.

## **Voltage Stability**

Voltages throughout the system must remain within an acceptable range at all times for system reliability. When power flows through a transmission line, the voltage drops. The voltage at the receiving end of a line is lower than at the sending end. If large amounts of power are transferred over long distances, the bulk transmission system must maintain adequate voltage at the receiving end. Voltage can also drop as a result of outages of critical facilities. If a sudden outage of a transmission line occurs, power will continue to flow at the same level, but on less efficient, alternative parallel paths. As a result, the voltage drop in the transmission system increases, and there will be an abrupt change in the voltage at the receiving end. Voltage drops or voltage fluctuations at the customer's end result in reduced system reliability.

## Frequency Stability

There are three power grids in the U.S. and all generators in each interconnected grid system operate in synchronism. That is, each generator operates at precisely the same frequency, which is 60 Hz in North America. System disturbances, such as load changes or facility outages, will cause the speed (i.e., frequency) of one or more generators to change relative to other generators. In addition, the magnitude of other frequency-dependent items, such as the load, also changes and causes imbalances in the system. Generator controls sense such changes and change the power output of the affected generators to synchronize the system. Frequency stability is compromised under two types of conditions: steady-state instability and transient instability.

- *Steady-state instability* occurs when the system cannot return to synchronous operation because of excessive power flows. The speed of some generators changes relative to others, causing system separation, a break-up of the transmission system, or a blackout.
- *Transient instability* occurs when a major disturbance - such as a short circuit on a transmission line or the loss of a large generating unit - is experienced, causing generators to oscillate relative to each other. If the system cannot damp the oscillations quickly, for example, by changing the output of generators, the oscillations will increase, causing large fluctuations in line loadings and system voltages. The result is the same as for steady-state instability: system separation, a break-up of the transmission system, or a blackout.

If power flows exceed dynamic limits over wide areas, the grid can exhibit unstable behavior. If not controlled, this can trigger large-scale outages. Dynamic grid stability is a critical issue for power system management. To maintain reliability, potential instabilities must be sensed and responded to quickly.

While transmission lines have a designed power handling capacity based on thermal limits, instabilities frequently limit maximum transmitted power to levels significantly less. This limits both the amount of power that can be imported from outside a region and the amounts that can be transferred from one region to another. The addition of significant remote generating facilities, much of it with low inertia, may have undesirable effects by reducing the overall system damping under sudden energy imbalance, such as generation trips.

## Technology Solutions

There are numerous options to increase the power flow capacity on existing power equipment, power circuits, and power system interfaces. The following three issues are basic to all approaches:

1. For overhead lines, an increase in power flow capacity is dependent on length, original design assumptions, environmental regulations, the condition of structures, and the type of conductors.
2. Transmission lines are terminated at substations by air disconnects, circuit breakers, and line traps. The power flow through all of the circuit elements must be limited to avoid damaging the line or the terminating equipment. The maximum allowable power flow over this circuit may be

limited by any one of the circuit elements. According to the current NERC rating methodology, a facility rating must be the minimum of all ratings between substations.

3. An increase in maximum allowable power flow through a component circuit or circuit element does not necessarily yield a higher rating for the complex interface, or from source to sink, when considered as part of a power system interface. This is because increased flow on an improved element may bump into another element's limits.

A variety of technologies is available to fully leverage and expand the physical capability of an existing transmission system infrastructure and its assets. These include the following:

- FACTS-based devices,
- HVDC converters and transmission lines,
- Enhanced series compensation,
- Use of dynamic compensation (DSC), and
- High-voltage DC (HVDC) transmission.

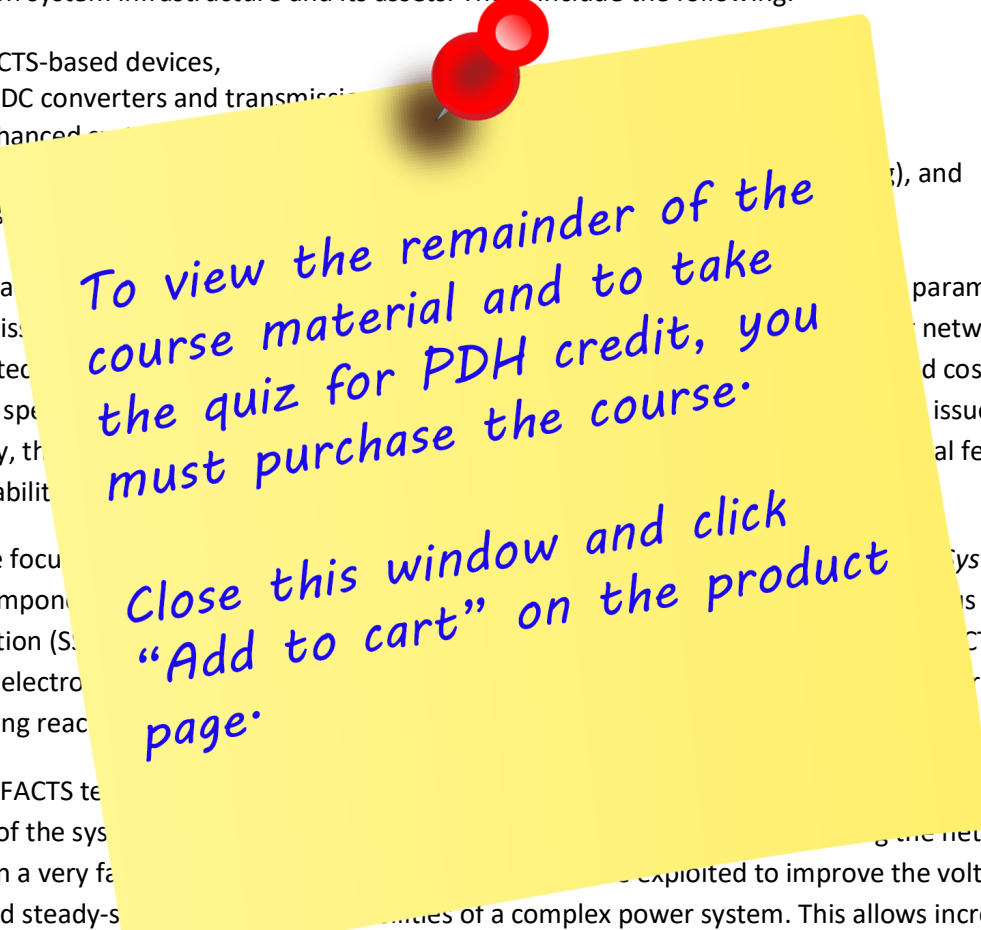
Although each of these technologies has its own set of parameters of network. As with most technologies, there are trade-offs between cost. In addition, a specific technology may have its own set of issues. Accordingly, the technical and economic feasibility and applicability of each technology must be evaluated.

This course focuses on the use of FACTS (FACTS) components such as Static VAR Compensator (SVC) and Dynamic Compensator (DSC) to use power electronics for controlling reactive power and controlling reactive power.

The use of FACTS technologies can increase the utilization of the system and improve the operating condition in a very fast manner. These technologies are exploited to improve the voltage stability and steady-state performance of a complex power system. This allows increased utilization of the existing network closer to its thermal loading capacity, thus avoiding the need to construct new transmission lines.

Static VAR Compensator (SVC) is a first-generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus using reactive power compensation. SVCs have been installed instead of traditional shunt compensation to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control.

Another FACTS controller is the STATCOM which is a solid-state shunt compensation device.



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