



# Dynamic Transmission Line Ratings

An Online Continuing Education Course for Engineers

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## Introduction

The electric grid is a complex system-of-systems that is responsible for providing safe, reliable, and cost-effective electricity to customers. Developed and built over the last 125 years, the U.S. electric power system has been called the largest man-made machine in the world. The electric transmission and distribution infrastructure and the energy delivery it facilitates is essential to the modern economy.



Whether the grid powers manufacturing and essential health services or our computers and cell phones, its omnipresence is felt most when it suddenly fails. Recently, investments in the grid have focused on improving its reliability, efficiency, and resiliency to meet the growing dependence on electricity across all sectors. This is a complicated task where generation and use must be balanced continuously, the ability to store electricity cost-effectively is limited, and energy consumption patterns are ever-changing.

The electric power system is typically divided into four categories of generation, transmission, distribution, and end-use. To meet consumer expectations of continuous access to electricity, utilities developed a system of generators, towers, wires, transformers, switches, and poles. In addition to the physical infrastructure, a centralized control system evolved in which large remote generators are coordinated and dispatched to ensure the reliable delivery of electricity to end-users through a vast network of high-voltage transmission lines and lower-voltage distribution systems. Entities known as *balancing authorities* and *system operators* have been tasked with the dispatch of generators to meet all loads while ensuring reliability and minimizing costs, a process known as *security-constrained economic dispatch*.

If a transmission system component, such as an overhead line, is operating at its physical limit, balancing authorities may need to run a more expensive generator over a less expensive one in order to meet safety and system reliability standards. This sub-optimal commitment and dispatch of generators are known as *congestion*. Balancing authorities and system operators attempt to mitigate congestion by forecasting demand and generator availability in the short term (e.g., through day-ahead and hour-ahead markets) and identifying system needs in the long term (e.g., through multi-year resource, transmission, and distribution planning).

The U.S. electric grid contains more than 200,000 miles of high-voltage transmission lines and roughly 6.5 million miles of local distribution lines that operate within a patchwork of Federal, State, and local regulatory jurisdictions. Reliability of the bulk power system—large generators and the transmission network—generally fall under the purview of the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation

(NERC), which issue and enforce mandatory reliability standards. Several professional organizations, such as the Institute for Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), and the International Council on Large Electric Systems (CIGRE) also issue guidelines and technical standards. These various standards provide the basis for the bulk power system that is key to ensuring the safe and reliable delivery of electricity.

The climate in the U.S. spans a vast spectrum, ranging from tropical to sub-arctic to desert, depending on location. This means the electric power system experiences many different temperatures and weather conditions daily and throughout the seasons of the year.

Additionally, the demand for electricity also changes by the hour, day of the week, and season with times of peak-load varying by region. In hot climates, home air-conditioning usage increases the overall load needed in the late afternoon during the hottest part of the year. In cold climates, home heating increases loads in mid-mornings and mid-evenings during the coldest part of the year. Weather conditions are also important to grid operations since they affect system loads, and extreme weather events can result in damage to infrastructure assets.

Parts of the electric grid are more than a century old, and 70 percent of the transmission lines and large power transformers are more than 25 years old. Along with aging infrastructure, the electric power system is evolving from one consisting of predominantly dispatchable generation sources (e.g., nuclear, coal, natural gas, and hydroelectric) to one having increasing percentages of variable generation sources such as wind and solar. The deployment of variable generation varies widely across the U.S. as well as the ability of the regional grid infrastructure to accommodate them. Additionally, the centralized control paradigm where generation is dispatched to serve variable customer loads is being challenged with greater deployment of distributed energy resources (DERs). These broad system changes have created a need for advanced solutions to help solve modern operational challenges.

*Transmission congestion* occurs when changes in demand or generation result in power delivery that reaches or exceeds the physical capacity of the transmission network. *Transmission constraint* refers either to the limit placed on a piece of equipment or an operational limit imposed to protect reliability that restricts these flows or to a lack of adequate transmission capacity to deliver expected new sources of generation without violating reliability rules. Power flows on transmission lines are limited for both electrical (e.g., voltage drop, phase, stability) and thermal (e.g., resistive heating, mechanical sag) reasons. Typically, these limits are calculated to ensure safety and reliability. Transmission congestion results in generation commitment and dispatch decisions that vary from a lowest-cost basis, ultimately increasing the price of electricity.

In most organized wholesale markets, the *locational marginal price* (LMP) of electricity is calculated by adding the system marginal cost (i.e., the incremental cost of electricity to meet the last MWh of demand based on economic dispatch), the congestion component (i.e., the cost associated with the local dispatch of more expensive generation to relieve the constraint), and the marginal loss components (i.e., transmission losses associated with delivering the increment of electricity). Therefore, the congestion costs are effectively paid for by the users of electricity. Congestion costs can be quite substantial, averaging \$5 billion per year.

Locational marginal price (LMP) of electricity is the price actually paid for electricity at different parts of the system.

Traditional solutions to alleviating congestion include expanding, upgrading, or rebuilding the electric infrastructure. In recent years, transmission expansion projects in the U.S. have averaged about \$20 billion per year, primarily due to the aging electric system.

Line reconductoring, which can be used in some situations to increase capacity on existing transmission right-of-way, cost from \$1 million to \$8 million per mile depending on the voltage class of the line. While these long-lead-time solutions may be needed in the long term, new and innovative technologies (e.g., Dynamic line rating, demand response, power-flow controllers, DER, and energy storage) may provide congestion relief in the near term at a lower expense.

Ultimately, the goal of the electric grid is to deliver safe, reliable, and cost-effective electric power. For each part of the system, there are numerous tools, technologies, and approaches to help accomplish this goal. In the distribution system, vegetation management and distribution automation are used to prevent and recover from interruptions. In the transmission system, a variety of contingencies are analyzed and planned for while phasor measurement units provide wide-area situational awareness.

One concept to relieve congestion and improve the efficiency of the electric system is by using *Dynamic Line Ratings* (DLR). Deploying DLR entails equipping circuits likely to benefit from significant capacity gains with sensors and using the resulting capacity increases when required and possible. Typical applications include:

- Easing congestions due to increasing load,
- Improving economic dispatch scenarios in N-1 contingencies,
- Integrating renewable/distributed energy sources without grid reinforcement,
- Deferring or avoiding uprating of circuits,
- Maximizing the use of alternate lines when main corridors are unavailable, and
- Maximizing transit on interconnectors and “bottleneck” topologies.

This course explains the concepts of line ratings, how dynamic line ratings are determined, and how they may be used to improve the operation of the electric power system. Chapter one is an in-depth discussion of transmission line ratings and calculations. Chapter two explains the technology associated with DLR, while Chapters three and four discuss the benefits and challenges of DLR implementation.

# Chapter 1

## Thermal Limits of Transmission Lines

Transmission line ratings are used to ensure that flows on transmission lines do not increase risks of reliability events or damage to lines or equipment. They can be expressed in terms of either electrical current or power-carrying capacity. A transmission line rating respects the most limiting applicable equipment rating of the individual equipment associated with the line, and in this course, we are only considering the thermal limit.

The electric current flowing through a transmission line heats the line due to the line's electrical resistance. Other conditions and phenomena can also tend to heat transmission lines, particularly solar irradiance. Conversely, some conditions and phenomena tend to cool transmission lines, particularly convective cooling from wind. Thermal transmission line ratings are generally negatively correlated to ambient temperature and solar irradiance intensity, but positively correlated with wind speeds. Conductor temperatures further depend upon conductor material properties, conductor diameters, and conductor surface conditions. These environmental and physical design factors are used when establishing the thermal limits of transmission lines.

Note: Transmission lines can be limited by their thermal rating, a voltage limit, or a stability limit. The advanced line rating approaches in this course only affect lines that are limited by a thermal rating.

Rating methodologies for transmission lines with no change in ambient condition assume steady-state conditions. These are typically "real-time" ratings where ambient conditions are constant over a 24-hour period. Figure 1 shows this relationship between Static Line Rating (SLR) and Dynamic Line Rating (DLR).

