Increasing Power Transfer Capability of Existing Transmission Lines

Jose R. Daconti, *Member IEEE*, and, Daniel C. Lawry, *Member IEEE*

***Abstract*—This paper initially describes the main constraints that limit the transmission system power transfer capability, as well as the existing methods to alleviate these constraints, such as transmission line uprating/upgrading techniques. It also discusses the main feasibility issues that need to be addressed aiming to evaluate when an uprating/upgrading solution should be recommended. After that, aspects of effectiveness, required technical analysis and usual methods for transmission line voltage and thermal uprating are presented. Finally, the dynamic thermal rate monitoring is emphasized as a good thermal uprating solution and its commercially available technologies are presented.**

***Index Terms*-- transmission lines, power transfer capability, voltage uprating, thermal uprating, upgrading, thermal rate monitoring.**

I. INTRODUCTION

According to the most updated statistics, the American power system is presently facing a load growth of approximately 2% per year. It is also known that in the last 20 years the generating capacity of the American grid raised 30% while its transmission capacity raised just 15%. Our transmission system is becoming progressively congested as a result of this mismatch between generation and transmission capacity. This congestion produces an increase in the electricity price paid by the customers.

Two main reasons are considered responsible for the slow increase of transmission grid capacity. The first one is the growing difficulty in getting permits for new lines. Some of the concerns that can be critically relevant in the permitting process are: transmission line visual impact, property devaluation, suspected health effects from EMF, impact on land use, impact on ecological systems and environmental impact of transmission line construction and maintenance. The second reason is the lack of investors interested in financing transmission projects. Other kind of projects can give them a better financial return for their money.

How, then, can electric utilities increase the power transfer capability of the existing transmission systems? To answer this question it is important to understand the power transfer capability constraints.

J. R. Daconti and D. C. Lawry are with Power Technologies, Inc.

II. TRANSMISSION SYSTEM POWER TRANSFER CAPABILITY CONSTRAINTS

A typical electric power system is comprised of a transmission system, a subtransmission system, and a distribution system. Transmission systems are responsible for the bulk power transfer and typically operate in the voltage range of 230 kV and above. Distribution systems supply the end-users and typically operate in the voltage range of 34.5 kV and below. Subtransmission systems make the link between them and typically operate in the voltage range from 69 kV to 138 kV.

The power transfer capability of the transmission systems is limited by current (thermal) related constraints, voltage related constraints and operating related constraints.

A. Transmission System Thermal Constraints

Thermal related constraints must be respected aiming to avoid overheating of transmission lines, underground cables, and transformers. Overheating underground cables and transformers can reduce their lives. Overheating transmission line conductors can produce aluminum annealing (loss of conductor mechanical strength) and excessive sags (violation of minimum conductor-to-ground clearance). For transmission lines, it is important to select an adequate maximum allowable conductor temperature, which will be related to a current rating. Transmission lines are typically submitted to three thermal constraints: a normal operation rating, a long-term emergency rating (4 hours) and a short-term emergency rating (15 minutes). It is possible to increase the power transfer capability of a transmission system by increasing the current-carrying capacity of its transmission lines and substation equipment. This is called Thermal Uprating.

B. Transmission System Voltage Constraints

Voltage related constraints must be respected aiming to avoid steady-state overvoltages and undervoltages. Overvoltages can cause insulation failure, short-circuits and bad corona performance, while undervoltages can produce inadequate operation of equipment and damage of motors at customers facilities. Transmission systems are typically submitted to two voltage constraints: a maximum operating voltage equal to 105% of the nominal voltage and a minimum operating voltage equal to 95% of the nominal voltage. It is possible to increase the power transfer capability of a transmission system by increasing the operating voltage within a voltage class, by controlling reactive power flows and consequently reducing voltage drops, and by increasing the operating voltage of its transmission lines and substation equipment. This is called Voltage Uprating.

C. Transmission System Operating Constraints

It is well known that: the power flow transfer between two areas can be limited by other parallel path flows; it is necessary to keep a reserve capacity in terms of generation and transmission aiming to be able to handle contingencies; it is necessary to limit the active and reactive power transfers to avoid problems of transient instability, steady-state instability and voltage instability. These are some of the usual transmission systems operating related constraints.

These constraints can be alleviated by using the following resources: changing connections of lines at substations, inserting switching stations along transmission lines, installing series capacitors and phase-angle regulators in transmission lines, using small inertia generators and distributed generation, installing FACTS devices, taking advantage of automatic voltage regulators and governor control systems, changing from "preventive" operating procedure to "corrective" operating procedure, and using on-line dynamic security assessment.

III. INCREASING POWER TRANSFER CAPABILITY BY MEANS OF TRANSMISSION LINE UPRATING

Performing a transmission line uprating can be very attractive in terms of getting smaller costs and shorter leadtimes when compared to building a new line. Besides that, it can postpone the need of new lines, reduce congestion costs and avoid unnecessary load shedding during contingencies. However, before starting the uprating task, it is important to evaluate some feasibility issues, as well as to choose the most appropriate type of uprating (Thermal Uprating or Voltage Uprating) for a specific transmission line. Each type of uprating requires different kinds of previous analysis and shall be done by its own methods. Sometimes a transmission line uprating also requires a line upgrading. Transmission line upgrading is related to physical modifications to the line.

IV. UPRATING/UPGRADING FEASIBILITY ISSUES

A. Technical Feasibility

For this kind of analysis it is important to consider at least the following points:

- System load requirements: It is important to evaluate for how long the uprated/upgraded line will satisfy the load requirements.
- Assessment of current conditions and life expectancy of transmission line materials: It is important to make this kind of evaluation for the main transmission line components, such as towers, foundations, conductors, insulators and hardware.
- Potential margins for uprating/upgrading: It is important to check electrical clearances, mechanical strengths, ROW width, as well as the possibility of compliance with the requirements of safety codes (e.g.: NESC), regulatory bodies and government agencies (e.g.: navigable streams, public lands, air lanes).
- Utility considerations: Sometimes electric utilities are not authorized to take the transmission line out of service to perform the necessary uprate/upgrade services. In these cases it is important to check if the mentioned services can be done with the line in service.

B. Economical/Financial Feasibility

For this kind of analysis it is important to consider at least the following points:

- Uprating/upgrading costs versus new line costs: It is important to remember that technical analysis of old lines usually requires data gathering and this can be very expensive and time consuming. Besides that, it is necessary to estimate what will be the need of the uprated line in terms of additional ROW. Other costs that can be relevant are related to construction (material and labor), maintenance and operation of the uprated line. Environmental costs are usually higher for new lines.
- Uprating/upgrading costs versus uprating/upgrading benefits

C. Social Feasibility

For this kind of analysis it is important to consider at least the following points:

- Environmental considerations: Usually not so critical when compared to new lines. However, it may be necessary to deal with historical societies, environmental groups, concerned neighbors, and so forth.
- Right-of-way easements: If significant changes will be made to the original line, it is necessary to check the validity of the previous right-of-way terms of use. It can be difficult to get licensing for the modified line. It is also important to check the existence of ROW encroachments and line crossings that would be unacceptable by the uprated line.

V. VOLTAGE UPRATING

This kind of transmission line uprating can result in a much higher rating increase than thermal uprating. This occurs because the transmission line power transfer capability increases with the square of the line nominal voltage. Besides that, transferring the same amount of power in a higher voltage level reduces the line current, and consequently, line losses and voltage drops. However, voltage uprating is typically more expensive than thermal uprating due to the need of also uprating the voltage class of the terminal substations equipment.

A. Effectiveness

This kind of uprating can be a good option when: the line loading is limited by voltage drop or stability considerations; the line has margins in terms of electrical clearances; the uprating can be done with minimal line modifications or it will be applied to several circuits simultaneously or the line design criteria can be relaxed.

B. Previous Analysis to Perform

Before proceeding with a transmission line voltage uprating it is necessary to analyze tower clearances, conductor-to-ground clearance, corona performance, electric fields, ROW issues, and sometimes structural strengths.

C. Usual Techniques

Some of the techniques used to perform transmission line voltage uprating are desbribed below:

- Addition of insulator units to the transmission line insulator strings
- Replacement of standard insulator units by polymeric or anti-fog units
- Application of strut insulators (or V strings) to prevent swinging of suspension strings
- Keeping appropriate conductor-to-ground clearances while increasing the transmission line operating voltage
    - Re-tensioning the existing conductors
    - Performing sag adjustments (cutting out conductor lengths; sliding conductor clamps)
    - Increasing the conductor height at the attachment support (converting suspension strings to pseudo dead-end strings)
    - Increasing the attachment support height
    - Raising towers
    - Moving towers
    - Inserting additional towers
    - Performing terrain contouring (rural areas)
- Bundling the original line conductor with another one, or replacing the line conductor by a bigger one, to assure a good corona performance
- Performing Line Compaction
    - Reducing distances between phases
    - Increasing distances between subconductors
- Converting a low voltage double-circuit line to a high voltage single-circuit line
- Converting a 3-phase double-circuit line to a 6-phase single-circuit line
- Converting HVAC lines to HVDC lines

Some of these techniques have large structural impacts.

VI. THERMAL UPRATING

A. Effectiveness

This kind of uprating can be a good option when the line loading is limited by thermal constraints and the line has margin in terms of maximum allowable conductor temperature.

B. Previous Analysis to Perform

Before proceeding with a transmission line thermal uprating it is necessary to analyze maximum allowable conductor temperature, conductor-to-ground clearance, magnetic fields, ROW issues, and sometimes structural strengths.

C. Usual Techniques

Some of the techniques used to perform transmission line thermal uprating are desbribed below:

- Performing Dynamic Thermal Rating Monitoring
    - Cheap Thermal Uprating Method
    - Data logger monitoring
      (seasonal cooling knowledge allows a better static rating re-assessment)
    - On line monitoring
      (real time cooling knowledge allows a real time line loading assessment)
    - Can be done just for the critical line sections/spans
- Raising the thermal limit imposed to the line by some inexpensive substation equipment (e.g.: disconnect switches)
- Raising the thermal limit by making similar the thermal limits of all line sections
- Keeping appropriate conductor-to-ground clearances while increasing the maximum allowable conductor temperature while
    - Re-tensioning the existing conductors
    - Performing sag adjustments (cutting out conductor lengths; sliding conductor clamps)
    - Increasing the conductor height at the attachment support (converting suspension strings to pseudo dead-end strings)
    - Increasing the attachment support height
    - Raising towers
    - Moving towers
    - Inserting additional towers
    - Performing terrain contouring (rural areas)
- Bundling the original line conductor with another one, or replacing the line conductor by a more conductive one, to increase the line current-carrying capacity

Some of these techniques have large structural impacts. Performing a transmission line thermal uprating can bring some impact to the substation equipment.

VII. DYNAMIC THERMAL RATE MONITORING

There are five main dynamic line-rating techniques: weather monitoring, tension monitoring, sag monitoring, line temperature monitoring, and the new PTI ThermalRate technique. The new monitor and method described in this paper comes as the result of experience with the present monitoring technology and methods of upgrading lines. Some of the drawbacks with the existing technology have been resolved with the ThermalRate monitor.

VIII. LINE RATING FUNDAMENTALS

The thermal rating of an overhead line is the maximum current that the line can handle without overheating. The line rating is a function of the weather conditions seen along the line, including wind speed, wind direction, air temperature, and sun. Other secondary influences might affect the rating, which are not considered in IEEE 738. These include the various forms of precipitation and indirect solar radiation.

Fig. 1 shows that over time a line has a distribution of ratings. This figure shows a whole year of actual rating data. Low ratings correspond to times of low wind speed and full sun. High ratings correspond to times of high wind speed crosswise to the conductor, no sun, and/or precipitation.

The thermal rating of most lines is based on sag. As electrical current increases through an overhead conductor, the line temperature increases and therefore the line sags. Each line has a minimum clearance to ground, which must never be violated for safety reasons. The thermal rating is the maximum current, which results in the line just sagging down to the minimum clearance. Any additional current would result in too much sag and a safety problem. Most utilities have adopted a set of semi-worst-case weather conditions that establish the line's "static rating". Common weather assumptions are 40 C (104 F) air temperature, full sun, and 2 ft/s (1.4 mph) wind speed crosswise to the conductor. The static rating for the line shown in Fig. 1 is only 920 amps. In reality, though, the actual line rating rarely falls to the static rating. It is even less likely that the line rating falls at the same time as the actual load is high. Therefore, much of the line's capacity is wasted.

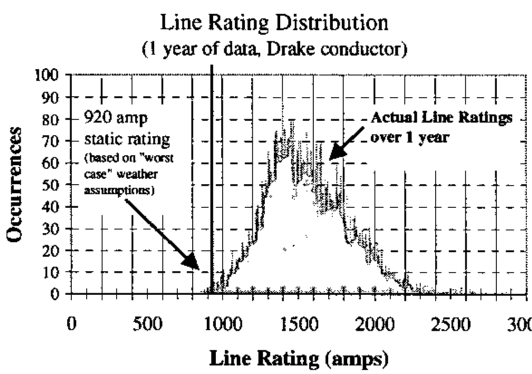

Fig. 1. Line rating

There are a number of methods to increase the capacity of a line. They are often expensive or even impossible, though, due to the required line outage. Monitoring approaches try to harness the capacity that already exists by permitting safe operations above the static rating of the line. The data can be used for either off-line rating analysis or in a real-time mode. In the off-line mode, the data can be used to perform a better evaluation of the static rating. Seasonal or time-of-day ratings can be created. Off-line analysis can also be used to determine how much can be gained by real-time operation. In the real-time mode, the ratings are reported to the operator in real-time. They can be posted on the existing SCADA display.

IX. GENERAL RATING CALCULATION METHOD

An equation to calculate conductor rating is developed by first recognizing that the total input heat (per unit length) to a conductor must equal the total output heat in the steady state. The conductor is heated by ohmic losses (I^2R) and solar input, and it is cooled by convection and radiation. Eq. 1 and Fig. 2 show this main "heat balance" equation:

$$Q_{solar} + I^2 R = Q_{convection} + Q_{radiation} \tag{1}$$

where:

Q_{solar} heat input due to solar radiation, W/ft.
I^2R heat input due to line current (R is a function of conductor temperature), W/ft.
$Q_{convection}$ heat output due to convection (a function of wind, air temp, conductor temp), W/ft.
$Q_{radiation}$ heat output due to radiation (a function of air temp and conductor temp), W/ft.

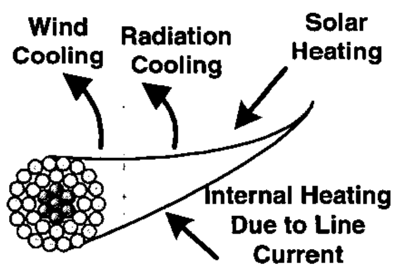

Fig. 2. Heating and cooling of an overhead conductor

Now, the equation can be reworked to solve for current as a function of the weather conditions. The $Q_{convection}$, $Q_{radiation}$, Q_{solar}, and R terms are all functions of weather conditions and of conductor temperature. If the weather conditions are measured and the conductor temperature is set to the maximum allowable conductor temperature, the calculated current is the rating current as shown in Eq. 2.

$$I_{rating} = \sqrt{\frac{Q_{convection} + Q_{radiation} - Q_{solar}}{R}} \tag{2}$$

X. NEW MONITOR PHYSICAL DESCRIPTION

The PTI's ThermalRate monitor determines the line capacity by measuring how the weather conditions heat and cool the conductor. The monitor consists of two aluminum rods which function as simple conductor replicas (Fig. 3A and 3B). The rods are chosen to be the same material and diameter as the line conductor. The rods are each about 2 feet long to account for temperature fringe effects on the ends, and they are separated by about 2 feet so that they do not affect each other's temperature. An internal sensor near the longitudinal center measures the temperature of each rod. The monitor is located near the line and pointed in the same direction as the line in order to experience the same weather conditions as the line itself.

One of the rods has a resistive heater (running at a nearly constant wattage) within it, which increases its temperature above that of the other rod. The weather conditions influence the temperatures of the two conductor replicas. By comparing the temperatures of two rods, the line capacity can be calculated and eventually supplied to the power system operator.

XI. CALCULATION DESCRIPTION OF NEW METHOD

In essence, by measuring the temperatures of both the heated and unheated conductor replicas and the wattage into the heated replica, the total cooling effect (mainly due to wind) can be calculated from the heat balance equation. Then, the rating can be determined using this wind in a second application of the heat balance equation. The calculation method for steady-state line rating is as follows:

Step 1. The heat balance equation (Eq. 1) is applied to the monitor's heated rod and is reorganized to solve for $Q_{convection}$:

$$Q_{convection} = Q_{solar} + I^2 R - Q_{radiation} \tag{3}$$

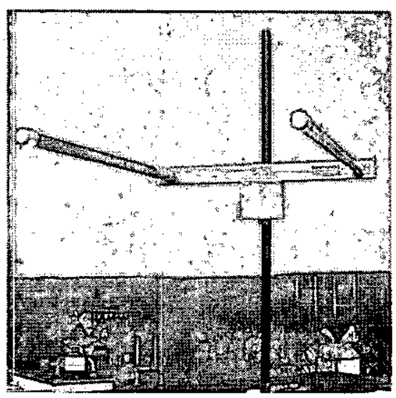

Fig. 3A. ThermalRate monitor

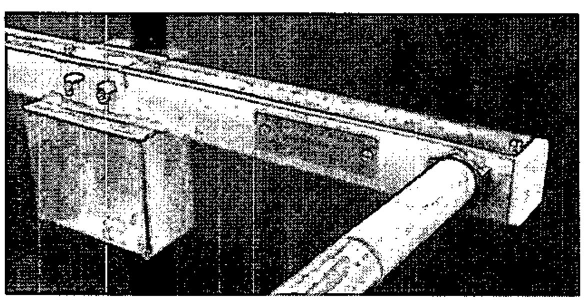

Fig. 3B. ThermalRate monitor

Step 2. It can be proven that the equivalent cooling will result if the solar input, Q_{solar}, is set to zero and the air temperatures within the $Q_{convection}$ and $Q_{radiation}$ terms are replaced by the measured unheated rod temperature. This eliminates the Q_{solar} term and also obviates the need to measure the ambient temperature.

Step 3. In Eq. 3, $Q_{convection}$ (watts per unit length) for the heated rod can be easily determined. The input power, I^2R, is measured. $Q_{radiation}$ is a simple function of air temperature (now unheated rod temperature), conductor temperature (now heated rod temperature), monitor emissivity, and monitor diameter.

Step 4. Knowing $Q_{convection}$, the "effective" wind velocity can be calculated from the IEEE 738 convection equations. This effective wind velocity is a wind speed and wind direction pair that results in the correct conductor cooling. For example, as far as the conductor rating is concerned, the wind speed at some angle is equivalent to a different wind speed at some other angle. A 2 ft/s wind speed perpendicular to a Drake conductor is equivalent to (meaning that it yields the same cooling effect and therefore rating) a 10.6 ft/s wind speed parallel to the conductor. The effective wind speed is typically calculated perpendicular to the conductor axis, and its calculation is also useful for additional weather analysis. If it is desired to determine the absolute wind speed and direction, the monitor must consist of 3 pairs of rods at 120-degree angles to each other, and the appropriate algorithm must be used. This approach is useful for calculating the rating of multiple lines extending out of a substation at different directions, or for lines that frequently change direction.

It is important to note that the monitor does not need to have exactly the same emissivity or diameter as the line itself. The effect of differences is to alter the unheated rod temperature, and if there are known differences, this value can be compensated.

Step 5. The line rating is now calculated using the heat balance equation applied to the line conductor (Eq. 2 is repeated here). The previously determined effective wind velocity is used within the $Q_{convection}$ term.

$$I_{rating} = \sqrt{\frac{Q_{convection} + Q_{radiation} - Q_{solar}}{R}} \tag{4}$$

where:

Q_{solar} is set to 0; and the air temperature terms within $Q_{convection}$ and $Q_{radiation}$ are set equal to the measured unheated rod temperature.

The conductor temperature terms within $Q_{convection}$ and $Q_{radiation}$ set to the user-input maximum allowable temperature.

The line emissivity and diameter are used, not the monitor parameters.

Resistance, R, is a function of conductor temperature and is calculated at the maximum allowable conductor temperature. The previously determined effective wind velocity is used within the $Q_{convection}$ term.

In summary, the three monitor measurements measure the effect of all weather conditions to allow accurate calculation of the line thermal rating.

XII. REFERENCES

[1] IEEE Std 738-1993, "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors", 1993

XIII. BIOGRAPHIES

Jose Daconti has worked for Power Technologies, Inc. since 2001. He has a MSEE Honors Degree from Federal School of Engineering of Itajuba (Brazil) and is a Cornell University HHH Fellow in the areas of Electric Power Systems and Electric Power Quality. Since 1978, most of his work has been concentrated in the areas of transmission line electrical design and electromagnetic compatibility. In 2000, he was nominated a CIGRE Distinguished Member. Mr. Daconti has been an IEEE member since 1993.

Dan Lawry has a BSEE degree from Clarkson University. He has worked for Power Technologies, Inc. since 1993 in the area of thermal uprating of overhead lines and other outdoor power equipment. Mr. Lawry has been a member of the IEEE since 1993.