TRANSMISSION & DISTRIBUTION WORLD

Can Utilities Squeeze More Capacity Out of the Grid?

Nov 1, 2003 12:00 PM
By Dale Douglass, Power Delivery Consultants Inc.

The recent Northeast blackout in the United States, followed by blackouts in England, Italy and Scandinavia, illustrates the complexity of our interconnected system. It can take months just to figure out what exactly caused these events, but we do know that a failure in one part of the system can rapidly affect geographically remote segments. A physical event such as a tree contacting an energized transmission line can play a significant role in bringing down our system.

Politics and History

Open-access legislation and deregulation have added uncertainty to providing sufficient transmission capacity for new generating sources. Power trading activities have resulted in increased, rapidly changing power flows, both under normal and emergency conditions. We have seen a reluctance to invest in bulk transmission, as well as major corridor and bottleneck upgrades.

When the North American power transmission system was being built-out, utilities would reinforce the grid by adding new circuits at ever-higher voltages (Fig. 1). This approach is less viable today, as we are still operating at or below voltage levels introduced in the 1970s. The construction of new lines has become more expensive and uncertain, which is primarily the result of public opposition. Now we must accommodate load growth and load displacement caused by open-access legislation.

Utility personnel are under considerable pressure to operate aging lines and equipment at higher levels (that is, closer to rating limits). This reduced margin between existing load and preset power flow limits has led to interest in new ways to increase rating limits under normal and emergency conditions. Unfortunately, increasing power flows on the bulk system typically result in increased power flows on some of the oldest lower-voltage circuits, especially during emergencies.

Power Flow and Rating Limits

In response to declining margins between power flows and rating limits, overloading may be prevented by increasing the rating limit of the existing circuit or by reducing the power flow on the existing circuit. To increase the rating of a circuit, we have access to many alternatives, depending on the limiting circuit element (such as an overhead line, a power transformer or a breaker) and whether the rating limit is caused by thermal, voltage or stability concerns. For example, an existing overhead line could be either reconductored or retensioned to increase the thermal rating. Forced cooling could be added to a high-pressure, fluid-filled underground cable. Shunt capacitance could be added to a circuit limited by voltage drop.

To decrease power flow on a circuit, passive or active methods can be used. A passive method would be the addition of a “parallel” transmission circuit to divert a portion of the present load. Passive power flow reduction typically adds to the capacity of the system. Because the added components are new, they also may increase the reliability of the system.

An active method example might be the installation of new, sophisticated technology that can control power flows. However, many have expressed concern that flexible alternating current transmission system (FACTS) devices, phase angle regulators (PARs), capacitors and static VAR compensators (SVCs) might negatively affect the reliability of the grid by inadvertently diverting power to less robust portions of the grid.

Traditionally, transmission system reliability is largely based on keeping power-flow levels in power lines and major substation equipment well below rating limits under normal and emergency operating conditions. The higher emergency loadings that typically occur due to planned or unplanned outages of major system components can then be handled by a well-designed grid without the need for load shedding or generation redispatch.

With the exception of adding new physical parallel circuits, all of these methods result in existing circuit components carrying more power under normal and emergency conditions. Even though none of the existing circuits may be overloaded, circuit components carrying increased load operate closer to their rating limits.

Line Length Matters

Line length typically drives rating limits. For example, long lines, typically 765 kV to 230 kV, are often stability-limited. As shown in Fig. 2, the steady-state stability limit of a typical 345-kV line (300 to 350 MW) is lower than the thermal limit (800 MW). The goal of active power-flow control devices is often to solve the stability problem and to allow power flow over such EHV lines at the higher voltage. Occasionally, these devices are installed to address thermal rating limits. Devices and techniques, including phase-regulating transformers, FACTS devices and automatic load shedding, can be implemented to increase power flow in long lines.

With medium-length lines, utilities more commonly face problems with voltage-drop rating limits that can be addressed with tap changer adjustments, shunt capacitors, synchronous reactors and physical modifications, such as the use of bundled conductor (to lower the series reactance). The lower-voltage (115 to 230 kV) lines are seldom long enough to generate stability problems and are usually limited by voltage drop.

Shorter lines, which are often the oldest and lowest voltage members of the bulk transmission system, are typically thermally limited. Methods to increase power flow on thermally limited lines include dynamic thermal ratings and reconductoring. Care must be taken because increased loading on these older lines and the associated substation equipment causes higher operating temperatures and may lead to splice failures, clearance violations or power transformer aging. For older 115- and 230-kV circuits, the rating limit is typically thermal. Operation at or near their thermal limit may result in accelerated aging of cellulose insulation in transformers or cables, loss of tensile strength in aluminum and copper conductors, and inadequate electrical clearance for lines.

Excessive voltage drop or stability problems are crucial considerations in reliable system operation, but excessive loading of thermally limited circuits can result in physical failures. Failures on thermally limited lines can worsen thermal and voltage drop problems on adjacent lines, which in rare cases cascade into regional blackouts.

In review, contingency outages of higher voltage circuits can lead to thermal overloads of the oldest parts of the transmission system. Physical failures from thermal overloads can lead to regional blackouts.

No Easy Fix

If we address stability and voltage drop concerns without adding to the physical system, we will find that existing system components will carry ever higher currents. The problem of handling higher power flows is particularly severe for lower voltage, thermally limited circuits under emergency load situations.

Given the increasing thermal stresses on these older, lower-voltage circuits, one would expect utilities to rate these components more conservatively, particularly if they are in questionable condition. Instead, because active load control methods are often uneconomic at 115 kV, utilities tend to search for ways to increase the rating of these elements without physical modification and without capital investment.

Aging Transmission Components

The aging of transmission components accelerates with time and temperature. This can be seen in the Arrhenius aging equations for modern transformers with 180,000 hours of “normal” life when operated at 110°C (230°F) winding hot spot temperature. The life of the same transformer when operated at 140°C (284°F) winding hot spot temperature is reduced to only 10,500 hours. A similar dependency of life upon temperature is found for insulated cable. The high-temperature exposure is unlikely to cause immediate failure, which awaits the next severe mechanical stress resulting from a high through-fault occurrence.

The aluminum or copper conductors of overhead lines lose tensile strength and permanently elongate at a high temperature. An all-aluminum conductor loses no significant strength at temperatures below 95°C (203°F) but may lose 25% of its tensile strength when subjected to a temperature of 150°C (302°F) for 1000 hours. Similarly, the normal sag increase of ACAR, AAAC or AAC conductor as a result of creep elongation over time may be many times greater after extended operation at high temperature.

Compression splices and transformer load tap changers are also sensitive to operation at high current levels. The level of degradation with time and temperature is difficult to quantify, though. This is particularly true for old compression splices made by unknown methods.

Corrosion of components is accelerated by high temperature, but one of the greatest difficulties involves quantifying the impact of high-temperature operation on a conductor or transformer that was manufactured 60 years ago.

For most transmission components, operation at an elevated temperature shortens life, but there is a great deal of uncertainty on how to weigh this reduction since most test data are derived for new components.

Re-rating of Existing Equipment

Shorter older circuits in the bulk transmission system are often thermally limited. As the whole system becomes more heavily loaded, there is great interest in increasing the thermal rating limit for such lines without investing large amounts of capital or compromising system reliability.

The most economic method of increasing the thermal capacity of an existing overhead line is to recalculate the line's thermal rating ("re-rate") with less conservative weather conditions. This has been done extensively in North America.

The justification for using less conservative weather conditions may be based on expediency or ignorance, on NOAA weather data, on field measurements of weather conditions in the vicinity of the transmission lines, or on detailed and extensive sag and tension monitoring records.

Line re-rating requires little or no capital investment, but the risks involved in re-rating circuits might not be evident until an actual load event occurs. In cases where the revised ratings are too high, the risk may not be evident until a post-contingency load occurs that approaches the new rating.

The table on page 43 illustrates the danger of re-rating lines without careful consideration of consequences. The line is assumed to have 45/7 795 kcmil Tern ACSR installed to a design temperature of 100°C (212°F). The second column shows the thermal rating calculated for the wind speed in the first column (and an air temperature of 35°C [95°F] with full sun). The third column shows the conductor temperature that results for a line current equal to the rating in column two when the actual wind speed is 0 ft/sec. The last column shows the amount by which the line design ruling span sag is exceeded for the still air condition.

From this table, we can conclude:

- Even with a conservative wind speed assumption of 2 ft/sec (0.61 m/sec), there is some risk of clearance infringement and exceeding the 100°C design temperature under still air conditions at high loads.
- If the line were re-rated for a 4 ft/sec (1.22m/sec) wind speed instead of 2 ft/sec (0.61 m/sec), there is a greater risk of clearance and overtemperature problems.
- With either rating, no problem exists if the line current does not exceed 770 A.

In almost any transmission line location, there are periods of still air. Also, the wind speeds shown are assumed perpendicular to the line. This is *not* a conservative assumption. Therefore, during periods of high loading, the sag of a re-rated line can exceed the design by the amount shown in the last column.

Dynamic Rating and Real-time Monitoring

Most power system operators have access to real-time estimates of bus voltage and circuit power flows through current and voltage monitors. Real-time monitoring of transformer oil or winding temperatures, sag or overhead line temperatures and underground cable temperatures is less common, although it appears to be increasing.

In the case of an overhead line, real-time monitoring of line tension or sag as well as line current and weather conditions can yield a dynamic rating for the line. Provided that the operator takes action to reduce the line current during these relatively rare times, when the weather is unfavorable and the line current is high, this method avoids the overtemperature problems of re-rating. Figure 3 illustrates a comparison of re-rating and dynamic rating methods. Re-rating amounts to accepting an increased probability of overtemperature events (the area where the upper tail of the load distribution overlaps the lower tail of the rating distribution). Dynamic rating involves a similar increase in rating but provides a warning to the operator when the curves overlap. Note the use of dynamic ratings reduces the probability of any overtemperature or sag infringement to near zero, lower than for even a conservative wind assumption of 2 ft/sec (0.61 m/sec).

The purchase and installation of line monitors (or power transformer top oil and winding hot spot monitors) is inexpensive compared to equipment replacement. However, it involves certain changes in operations and maintenance of both the monitors and communications links. It also results in increased average operating temperatures for the equipment.

Real-time monitoring of lines and power transformers also allows the detection of imminent failure events. By performing an ongoing comparison of calculated and measured oil or winding temperatures, cooling problems can be detected before the power transformer is damaged. By noting the variation of tension with temperature, breaks in the steel core of an ACSR line or structure support failures can be detected remotely.

Reconductoring Lines

Existing lines can be reconductored if the supporting structures are in good condition, although replacement of hardware and insulators is probably more sensible than reuse. If the replacement conductor tension and transverse structure loads can be kept similar to those of the original conductor, the line can be reconductored without needing to replace or extensively reinforce structures.

Figure 4 illustrates how an original 200-mm^2 (397.5-kcmil) aluminum conductor rated for 500 A at 75°C (167°F) can be replaced by either a larger 400-mm^2 (795-kcmil) conductor operating at 100°C (212°F) or by a high-temperature low-sag conductor operating at 200°C (392°F) to double the original line rating to 1000 A.

The difficulty in using the larger conductor is that it will almost certainly increase the tension and transverse structure loads to an extent that requires reinforcement or replacement. The advantage to the system is that this larger conductor will serve to reduce ohmic losses and average operating temperature.

The advantage of recently developed high-temperature low-sag conductors is that the replacement conductor can be about the same diameter as the original, and the existing structures can be reused without the need for reinforcement. The increased thermal rating is obtained by running these conductors to temperatures as high as 200°C while not exceeding the maximum sag of the original conductor. Questions naturally arise about the long-term viability of conductors intended for use at such high operating temperatures. Extensive test data are usually required from the manufacturer.

Let's Get Busy

Given the many constraints on building and financing new transmission facilities, the increased use of the various “invisible” methods of increasing bulk transmission circuits power flows appears likely. As a result, the normal power flows and post-contingency loading of the older, lower-voltage circuits in the system also will increase. The combined effects of increased thermal and electrical stress on the high-voltage transmission system are likely to result in reduced physical reliability.

Potential Danger of Re-rating Lines Without Consideration of Consequences

>

Assumed Wind Speed ft/sec	Rating@100°C 45/7 Tern ACSR amperes	Conductor Temp for 0 ft/sec (still air) with current = rating@100°C	Added sag in 1000-ft span feet
0 (still air)	770	100°C	0
2	1010	135°C	3.3
4	1185	165°C	6.0

This trend may be slowed or stopped through the application of up-rating methods that reduce or limit the thermal and mechanical stresses and provide the system operator with better information concerning the condition and thermal/mechanical state of key components.

Certain changes in the traditional design, construction, maintenance, and operation of lines, cables and substation equipment will be required. Key changes include developing improved thermal/mechanical models of power equipment, increasing availability of real-time and historical field data records, and replacing aged, marginal equipment is part of the process of increasing power-flow limits.

Dr. Dale A. Douglass is a principal engineer with Power Delivery Consultants Inc., based in Niskayuna, New York. Douglass has 30 years of experience in transmission line engineering and conductor design, having worked with Power Technologies Inc., Kaiser Aluminum and Bell Laboratories. He is presently the convener of CIGRE Working Group B2-12 on Electrical Aspects of Transmission Lines and vice chairman of IEEE's Towers, Poles and Conductors Subcommittee. He has performed many studies of overhead line sag-tension, high-temperature operation, the dynamic rating of lines and power transformers, and both current and voltage upgrading of existing lines. Douglass is a fellow of the Institute of Electrical and Electronic Engineers.
da.douglass@ieee.org