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Physical and Electrical Effects to Nearby Facilities When Applying Dynamic Line Ratings to Transmission Lines

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SUMMARY

Applying dynamic line ratings (DLR) to an existing transmission line can have various effects on nearby facilities. These changes are largely due to the change in the line currents, but also due to the increased sag. This paper discusses generally what DLR is and the physical effects are on the line itself. Further discussion includes impacts on adjacent facilities, both physical and electrical, as well as the relative amount of influence. This discussion provides practical information and items to consider for entities looking at applying DLR to an existing transmission line, even if no physical changes are made to the conductors or nearby structures. Similar impacts are present for any uprating of a transmission line. In addition, the paper provides insights to regulating entities to develop necessary standards for DLR implementation or update existing standards, in order to maintain safety to the public and ensure nearby facilities are not compromised.

KEYWORDS

Dynamic line rating, DLR, grid operations, wind power integration, transmission lines

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INTRODUCTION

Most overhead transmission lines are conventionally rated with a static continuous rating, the maximum amount of current the line conductors can carry without violating safety codes or damaging the conductor. The static ratings are normally set considering worst environmental conditions (e.g., low wind speed, high ambient temperature, and high solar radiation) [1]. This approach underutilizes line ampacity since the worst environmental conditions exist only for a short period of time over the year/season [2]. Some electric utilities seasonally adjust the static ratings to account for different environmental conditions [3]. Even though seasonally adjusted rating results in better utilization of line ampacity, the weather-adjusted ratings cannot take full advantages of additional line ampacity headroom available from local weather conditions [4].

Since local environmental conditions are most often less stressful compared to the design considerations of static or seasonally adjusted static rating, there is typically additional headroom on line ampacity utilization resulting from inherent cooling of the conductors. Therefore, real-time monitoring of environmental parameters and electrical systems can help to accurately estimate the thermal rating of the transmission lines, thereby maximizing utilization of additional ampacity headroom. Dynamic line rating is a recently developed concept in which ratings are dynamically computed in real-time considering natural cooling of the line conductor [5]. DLR, which is calculated based on real-time weather and transmission line operating conditions, and are often, but not always, greater than the static/seasonally adjusted ratings [2]. Transmission system owners and system operators can use DLR to make informed decisions on improved transmission line capacity usage [6]. The key benefits of a DLR system identified by the U.S. DOE include: 1) improved transmission line efficiency, 2) decreased/deferred capital costs requirements through improved utilization of existing transmission lines, 3) decreased transmission line congestion costs, 4) reduced greenhouse gas emissions by facilitating increased integration of renewables, and 5) increased situational awareness and operational flexibility of a transmission line [8]. Due to the natural synergy between wind generation and increased conductor ampacity at times of high local wind, DLR serves as an excellent mechanism to increase wind energy hosting capacity of the existing transmission lines [7].

Recently, transmission line DLR is gaining significant momentum from both the research community as well as from electric utilities and system operators. In fact, the U.S. Department of Energy (DOE) identified DLR as one out of eight smart grid transmission and distribution infrastructure metrics [5]. In addition, professional organizations, such as IEEE and CIGRE, have developed standards (e.g., IEEE Std 738) and formed working groups and task forces to define methods for computing temperatures of overhead lines with time varying weather conditions [9]-[11]. Recent technological advancement [12]-[13], and operational integration of electric utilities have proven the effectiveness of the proposed method [3]-[6]. Field demonstrations on influence of environmental conditions for DLR [14] and its potential application for improved wind energy integration [15] have demonstrated significant improvement on ampacity headroom of the existing transmission lines. In addition to technological aspects, the authors in [16] presented the regulatory framework and requirements for effective deployment of DLR technology. Even though DLR results in a number of benefits, it is accompanied with several concerns that need to be closely considered while implementing DLR. As shown in Fig. 1, key concerns of applying DLR are associated with increased current that may create several impacts, including increased electric/magnetic field, increased sag, and decreased conductor strength. However, none of the recent literature has investigated effects of DLR to nearby facilities. This paper discusses the physical and electrical effects of applying DLR to existing overhead transmission lines into various nearby facilities and on the line itself. This study provides insights on practical information and items to consider for electric utilities looking to apply DLR, and identifies some aspects that need to be considered by regulatory entities and electric utilities for ensuring effective deployment of DLR.

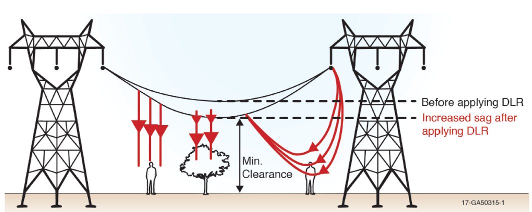

Fig. 1. Conceptual overview of the impacts of DLR to nearby facilities

HIGH-LEVEL OVERVIEW OF DLR

This section presents a high level overview of weather-based DLR developed by Idaho National Laboratory (INL). Since ampacity of transmission lines is closely correlated with its ability to dissipate heat produced by the Joule effect into the environment, the level of ampacity utilization improvement greatly depends on environmental conditions (e.g., ambient temperature, solar radiation, wind speed, and wind direction) and their relative variations with respect to assumed environmental considerations during design stage. As such, the key idea behind DLR is a heat energy balance equation which is mathematically expressed as:

$$I^2R(T_c) = q_c + q_r - q_s$$

where q_r, q_c, and q_s are the radiative heat loss, convective heat loss, and heat gain from the sun through the solar radiance, respectively; R is the conductor resistance, which is a function of conductor temperature T_c; and I is the current through the conductor. As the heat losses (q_r, q_c, and q_s) greatly depends on environmental conditions such as ambient temperature and wind speed/direction, the line ampacity can also vary significantly with the variation of those parameters. A typical variation of line ampacity with ambient temperature is illustrated in Fig. 2. It can be observed that there is huge difference (nearly 100%) on current carrying capacity of the conductor with the variation on ambient temperature shown. This demonstrates why static ratings, computed based on worst environmental conditions heavily underutilize transmission line ampacity.

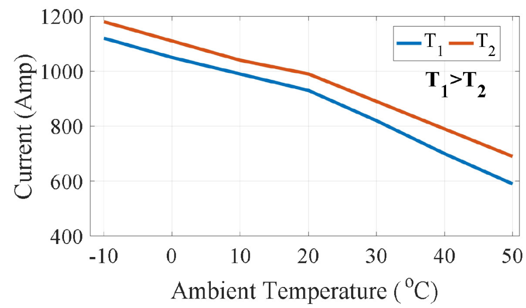

Fig. 2. Variation of ampacity as a function of ambient temperature

INL developed weather-based DLR system for computing real-time thermal rating of lines based on measured weather data and line operating conditions. It primarily consists of two major components: WindSim and general line ampacity state solver (GLASS). WindSim is a wind simulation software that works based on a computational fluid dynamics (CFD) model and is used for computing weather parameters at mid-points between weather stations, whereas GLASS is a computational engine and the heart of the DLR system which computes the actual line ratings in real time considering IEEE Std 738. Systematic assessment of numeric data (SAND) is a tool for organization and pre-processing of historical weather data to make it compatible to the format GLASS can consume. Since the key focus of this manuscript is not on detailing DLR, the details of DLR implementation are not considered. The details of DLR methodology and its components can be found in [2].

PHYSICAL IMPACTS

This section presents physical impacts of applying DLR to an existing transmission line. Most of the physical impacts of DLR to the overhead transmission lines are associated with the rise in conductor temperature. Therefore, the temperature of overhead transmission line conductors is limited to avoid the excessive sag, loss of tensile strength of the conductor, and physical deterioration of the connectors, using DLR or static ratings. As such, maximum acceptable conductor temperature, TC_{max}, is often used for the computation of the line current to prevent conductor temperature exceeding TC_{max}.

Increase in Sag

Although the conductor's temperature is dependent on the electrical load, it is strongly influenced by environmental conditions, such as wind speed/direction, air temperature, and incident solar radiation. Depending on the mechanical tensile strengths of the conductor, changes in temperatures can significantly change the sag. In fact, a rise in temperature causes the conductor to elongate which, in turn, increases the sagging. A pictorial view of an overhead line and its sag and clearance is provided in Fig 3, whereby the sag S is graphically represented with a parabolic curve and mathematically formulated by the following catenary equation:

$$S = \frac{mgL^2}{8H}$$

where m is mass per unit length, L is the span length, and h is the horizontal component of the conductor tensile force, which in turn depends on the thermal-tensional equilibrium of the conductor as follows:

$$A(T_{c2} - T_{c1}) + \frac{B}{H_1^2 - H_1} = \frac{B}{H_2^2 - H_2}$$

where T_c is the conductor temperature and A and B are the parameters which depends on conductor properties, including thermal elongation coefficient, Young's modulus, cross sectional area, conductor mass and span length. Please note that subscripts 1 and 2 refer to two different states. It can be seen that there is a direct relationship between sag and conductor's temperature.

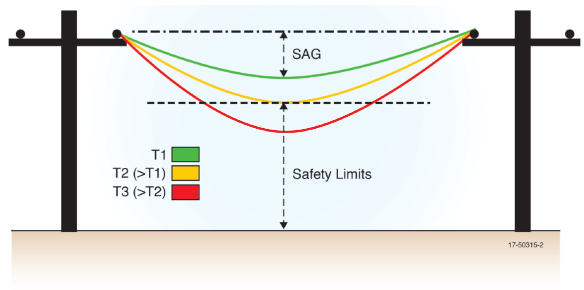

Fig. 3. Variation of sag as a function of temperature [16]

One of the key regulatory requirements for overhead transmission line conductors is to maintain the minimum clearance to ground, buildings, or other structures. However, the increase in temperature resulting from increased current through the conductor due to DLR may result in increased sag, which ultimately decreases the electrical clearance to the nearby facilities. Given that the thermal time constant for bare overhead conductors is in the range of 10 to 20 minutes, sag clearance problems can develop quickly following the exceedance of TC_{max}, thereby threatening the public safety.

Decreased Conductor Strength

Decreased conductor strength is one of the key potential impacts of increased line current resulting from DLR. In fact, due to inherited risk in the accurate prediction of weather conditions over the line corridor, there is always some risk of exceeding TC_{max}. While exceeding TC_{max} over a short period may be acceptable, the exposure to excessive high temperature over an extended period may damage the conductor or decrease the strength of the conductor. Such reduction in tensile strength of conductor increases the risk of the conductor being damaged, especially during severe ice and wind load conditions. It is worth mentioning that the loss of strength due to aluminum annealing is less of a concern with steel core aluminum conductors having a core area greater than 7% of the aluminum area [11].

Aging of Connectors

Connectors, including clamps and insulator strings, are often used in the transmission system to support and tighten the conductors to the transmission line structure. As the primary purpose of the insulator is to avoid the circulation of electrical current from the conductor to the tower, the increase in conductor temperature stresses the insulator and eventually contributes to the faster aging of the connectors. Depending on the design consideration and limiting aspect of TC_{max}, the first impacts of exceeding TC_{max} can be one or more of the following: aging of connectors, loss of conductor strengths, or increased sag. If the TC_{max} has been set to avoid aging of conductors, exceeding TC_{max} will directly impact the connectors. In fact, the connectors can lose breaking strength with excessive cycling to high temperatures. One of the key approaches to prevent failure due to increased conductor temperature cycling is to shunt or reinforce the connectors with other devices.

Potential Risks to Implement DLR

The potential risks of implementing DLR arise from inaccuracies in predicting weather and grid operating conditions.

Weather Prediction Risks: As DLR depends greatly on the weather conditions (e.g., wind speed, ambient air temperature), any uncertainties on weather parameter predictions will introduce risks of TC_{max} exceedance. Even though the ambient temperature along the line corridor can be predicted with reasonably high certainty, prediction of wind speed and direction within line corridors are very challenging, especially during low speeds with high turbulences. In order to address the potential impacts resulting from the DLR, weather prediction risks should be integrated in the DLR. However, there exists some risk of exceeding the temperature even with the static rating, and integration of weather forecasting to DLR can help to reduce the risk.

Line Rating Prediction Risks: The risk associated with line rating prediction is normally determined by measuring or calculating the frequency and magnitude of conductor temperature excursions above TC_{max}. However, as it is practically difficult to measure the conductor temperature at every span along the line corridor, the common practice is to measure weather conditions at one or more points within a line corridor to derive the line conductor temperature. In particular, the conductor temperature can be tracked using methods described in IEEE Std 738. However, there are inherited risks in terms of accuracy in predicting line temperature development over the conductor, thereby requiring effective integration of predicting tools to DLR deployment. Nonetheless, computational fluid dynamics enhanced weather-based DLR together with temperature measurement at critical lines can help to reduce the line prediction risks.

ELECTRICAL IMPACTS

Applying DLR to existing transmission lines affects adjacent facilities for two main reasons: more current is flowing in the line, and the conductor is closer to the ground a larger portion of the time (and possibly at maximum sag) due to Joule heating. These effects combine to multiply the effects of each other. The following sections discuss several of the aspects that can increase due to higher line ratings.

Electromagnetic Fields (EMF)

EMF consists of two components, electric fields and magnetic fields. The field strengths near ground level are of primary interest to the public and are proportional to the distance from the conductors. With increased sag if applicable, both field strengths will increase a small amount near the ground. Since the magnetic field is directly proportional to the current and inversely proportional to the distance, the magnetic field near a conductor will increase when either the line current increases or when the line sag increases. Because line sag is related to the line current through Joule heating, both effects are expected to be present in conductors using higher line ratings. Since magnetic fields are of interest to the public, calculation of the new expected field strengths is recommended.

Electric fields are proportional to the voltage of the line, and therefore only increase slightly due to the increased sag of conductor if applicable. Some locations have limits for electric field strengths, but typically only EHV transmission lines come close to these limits, and as a result the slight increase is usually not directly a concern.

AC Interference on Adjacent Facilities

Magnetic fields will couple onto any ferrous metallic objects that are parallel or semi-parallel to a transmission line. This inductive coupling is commonly referred to as AC interference and results in a current flowing in the adjacent object. Because of the current flow and the resistance of the material, a voltage rise will occur along the parallel object, particularly if the object is partially insulated from ground.

Objects commonly of concern for AC Interference include railroads, pipelines, and fences. Railroads are electrically partially insulated from ground through the ties and ballast rock material as the rails are used as part of a signaling system. Many pipelines are coated with an insulating material for cathodic protection purposes. Since these objects can parallel for very long distances, they may be exposed to significant induction.

Induction can present safety concerns to workers or the public, as well as equipment damage or misoperation concerns. Buried pipelines have limited exposure to individuals under normal situations, but rails are continuously accessible. Elevated voltages on a rail system can also result in signaling misoperation (e.g. crossings signals incorrectly indicating a train is coming). Elevated voltages on a pipeline could result in accelerated AC corrosion of the pipeline through any damaged coating.

Design guidelines for mitigation of AC interference from transmission lines on railroads and pipelines are often based on maximum rating of a line for safety aspects and typical loading for other aspects. Since both of these may increase on a line with DLR, induction (currents and corresponding voltages) will increase proportionally. Because many older facilities did not have analysis performed, even a small increase may present issues to a system that was performing marginally previously. The fact that DLR may allow the line to be more regularly heavily loaded increases the risk of safety concerns, misoperation, or damage, and these effects should be considered and analyzed if appropriate.

Capacitive Coupling

Electric fields will couple onto ungrounded objects in the vicinity. One common scenario is a vehicle underneath the line. In the U.S., the National Electric Safety Code requires that a short circuit current discharge due to capacitive coupling be limited to 5 mA [19]. If the transmission line was operating close to this limit before and the sag increases, the lower conductor heights and corresponding increase in electric fields could exceed the limit. Similar to inductive coupling, capacitive coupling can cause interference on other adjacent facilities. The methodology is the same as discussed in the previous section. However, many parallel or crossing facilities, such as pipelines, railroads, and metallic fences are buried or effectively grounded and therefore no capacitive coupling can occur. Ungrounded fences (such as barbwire on wood posts) may be subject to capacitive coupling, but again, increases will be minimal.

Corona Effects

Corona is an ionization of air molecules and occurs on transmission lines at higher voltages due to high electric field gradients on the conductor. The effects of corona include radio frequency interference (e.g. AM radio noise) and audible noise. Because DLRs do not change the voltage of the line, corona effects are generally minimally increased, and only increase due to the conductors being closer to ground. These increases are typically imperceptible, especially at the edge of the right-of-way.

Effects on Nearby Communications Facilities

Communications facilities are not directly impacted by the current flowing in a transmission line; however, it is possible that the change in sag could affect some facilities. If very near an AM broadcast signal, the modified physical shape of the transmission line could result in AM re-radiation, distorting the signal pattern. Similarly, if a very high frequency microwave or terrestrial satellite is broadcasting under and very near the transmission line, enough of the signal may be blocked by the lower conductors. These instances are rare but can occur if communications facilities are very near the transmission line.

REGULATORY ASPECTS

In addition to the physical and electrical impacts of DLR, there are safety related consequences which should be respected at any cost. As such, regulatory entities need to develop standards to account for the physical and electrical impacts of the DLR. The first and foremost concern on implementing DLR includes public safety, which is very much correlated with the increased sag resulting from increased current flow due to DLR. However, according to Federal Energy Regulatory Commission (FERC) and North American Reliability Corporation (NERC) perspectives, electric utilities should keep the sag to minimum value to ensure public safety [20]. Breaching of any public and technical aspects may incur huge economic penalties to the utilities. As such, the DLR should integrate public safety and economic penalties into account while quantifying its cost-benefits.

As DLR cannot be obtained experimentally, they are calculated based on TC_{max} and estimation of local weather conditions along the line corridor. However, any discrepancies in the prediction of weather conditions may cause the conductor temperature to exceed TC_{max} for some percentage of the time. However, to maintain the line integrity, the risk of exceeding TC_{max} should be less than 5% according to the contemporary regulation set forth by NERC [20]. The impacts of exceeding TC_{max} may vary depending upon the design consideration of the lines. If TC_{max} is designed to limit conductor sag, exceeding TC_{max} can lead to electrical flashovers to vehicles or underbuilt lines, thereby threatening the public safety. However, if TC_{max} is designed to limit annealing of the conductor, exceeding TC_{max} may lead to tensile failures especially during high wind and ice loading conditions. As such, the need to maintain the public safety is vital for clearance limited lines, thereby making it necessary to use real-time line corridor monitors or similar technologies.

CONCLUSION

There are several possible impacts to nearby facilities when DLR is applied to existing overhead transmission lines. This paper summarizes key physical and electrical impacts of DLR to nearby facilities and a transmission line itself. It also discusses their relative influence on the nearby facilities based on the amount increased line current. The analysis provides practical information and items to consider for electric utilities looking at applying DLR to an existing transmission line, even if no physical changes are made to the conductors or structures. This also helps regulating entities to develop required standards to ensure safety of public and nearby facilities while implementing DLR.

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