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Online Dynamic Assessment of Transmission Ratings for Transmission Constraint Management in Power System and Market Operations

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SUMMARY

In North America regional transmission organizations (RTOs) like PJM, Midcontinent ISO and ISO New England are fundamentally reliant on security constrained unit commitment (SCUC) and security constrained economic dispatch (SCED) to optimally dispatch generation resources to serve the native load in large geographical regions. Facing the challenges posed by the smart grid, RTOs are in the process of designing and implementing the next generation of dispatch systems with broader capability and higher economic efficiency. More accurate assessment of transmission flow limits will directly impact the efficiency of system and market operations. Transmission systems are constrained by the capacities or the ratings of their transmission lines. Transmission rating is defined as the maximum current that the transmission line can safely carry without damaging the conductor. Transmission owners and operators calculate static thermal ratings of their transmission lines for normal, long-term emergency (LTE), and short-term emergency (STE) conditions. These static ratings are updated infrequently and, as a result, they are typically conservative based on worst weather conditions. Dynamic line rating (DLR) is the current limit determined by real weather conditions surrounding the conductor. DLR has the potential to increase the line rating and reduce transmission congestion. Another way to safely increase the utilization of transmission lines by accounting for system's post-contingency ramping capabilities including post-contingency corrective actions. This concept is called adaptive transmission rating (ATR). This paper proposes to incorporate both DLR and ATR in transmission constraint management for power system and market operations. The methodologies of both DLR and ATR are first discussed separately. Preliminary results of DLR and ATR are presented. By combining DLR and ATR, we present a comprehensive solution for assessing real-time transmission ratings.

KEYWORDS

System operations, dynamic line ratings, adaptive transmission ratings, smart dispatch, constraint management

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INTRODUCTION

Recent emphasis of low carbon energy mix and demand responsiveness have brought new challenges and concerns for the secured operation of stressed power systems. Unlike conventional generation resources, outputs of many of the renewable resources do not follow traditional generation/load correlation but have strong dependencies on weather conditions, which from a system perspective is posing new challenges associated with the monitoring and controllability of the demand-supply balance. In many cases, wind farms are installed far away from the load centers and concerns over how much variable wind generation that can be integrated into the operation of a power grid depend on the ability to transport the power generated by these wind farms over the grid and to manage transmission congestion. As the penetration of renewable generation grows, a smarter dispatch system that can provide higher transfer capability without compromising system security and reliability is very desirable.

TRANSMISSION CONSTRAINT MANAGEMENT IN SMART DISPATCH

Smart Dispatch (SD) was envisioned to be the next generation of resource dispatch solution for smart grid [1]. One of the core functions of resource dispatch is the so-called security-constrained unit commitment (SCUC) and security constrained economic dispatch (SCED). SCUC and SCED are designed to provide dispatchers in large power grid control centers with the capability to manage changes in load, generation, interchange and balance them simultaneously subject to transmission security constraints on an intra-day and near real-time operational basis. Transmission constraint information is a critical input to SCUC/SCED. It does not only impact the feasibility of the solution but also the optimality of it as well. With the latest State Estimator (SE) solution as the starting point of initial dispatch position from the energy management system, transmission and generation outages from an outage management system and transmission constraints from a transmission constraint management system, SCUC/SCED can forecast system conditions and generation patterns for various look-ahead timeframes. Figure 1 shows the system overview of transmission constraint management (TCM) in SD.

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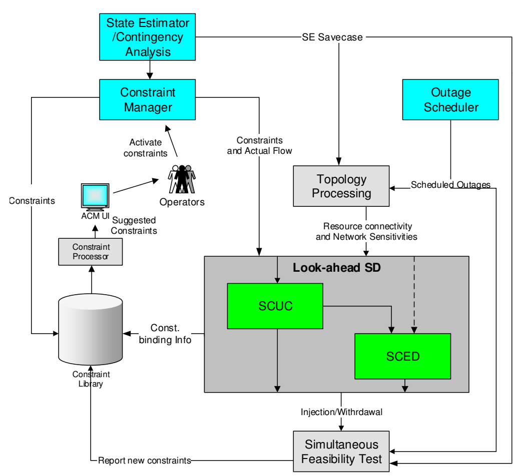

Fig. 1. Transmission Constraint Management in Smart Dispatch

Typically, grid base-case and contingency transmission constraints are in the following form

$$\sum_{i} a_{l,i}(P_i - D_i - d_i \times FD) \le L_l^{\max} \qquad (1)$$

where P_i, D_i are the decision variables for generation dispatch and load dispatch at bus *i,* respectively; FD is the fixed demand and d_i is the load distribution factor for fixed demand ; $L_l^{\max}$ is the grid security limit for constraint *l*; $a_{l,i}$ is the sensitivity of constraint *l* with respect to bus *i*. The determination of DLR and ATR will directly impact the value of $L_l^{\max}$. It is important to note that only thermal limitations are addressed here. Consideration of transient stability limit or voltage stability limit is outside the scope of this paper. In addition, TCM provides analysis of the fundamental components of constraint control by evaluating near-term line loading trends and adapting constraint control strategy based on current conditions. This tool deconstructs the causes of MW flow on transmission equipment based on $a_{l,i}$, which can be used to predict future loading on the transmission system. This predictive information can be utilized to reduce the number of "hard" limits that must be honored by the SCED engine. TCM can also use experience with transmission line load trends to adapt constraints presented to the optimization engines to better align transmission control requirements with actual operating conditions. The adaptation of transmission constraints improves the performance of the engine and can reduce the cost of controlling the system through more precise transmission loading control [1].

DYNAMIC LINE RATINGS

Electric transmission lines are essential to delivering electricity to customers. A transmission line is constrained by its rating, which is the highest current that the line can safely carry without damaging the conductor. Transmission lines, which may be tens of kilometers long, are normally designed in line sections consisting of multiple spans. Weather conditions such as ambient temperature, wind speed, wind direction and solar radiation can affect conductor temperature and cause the capacity change along a line and throughout a day. Based on existing studies [2], wind is the most influential parameter that varies along a line and causes significant impact to the line rating. Traditionally, static line rating (SLR) of a line is conservatively calculated under the "worst-case" operating conditions (e.g., 40^{o}C summer ambient temperature, 0.6 m/s perpendicular wind speed and full sun) based on the heat-balance equation [2]. These conservative assumptions may restrict the line capacity whenever the real weather condition is less stressful. Recently, the dynamic line rating (DLR), which uses measurements of environmental conditions and line characteristics (e.g., conductor temperature, sag and tension), is shown to improve the efficiency of transmission network and mitigate system congestion [2]. Based on the types of measurements (Figure 2), DLR methods are generally categorized as weather-based, conductor-based and sag-based methods [2], [3]. Among them, weather-based method, which only collects weather measurements from weather sensors installed on towers or nearby weather stations, is straightforward and used in this paper.

Using predicted weather conditions and/or line characteristics to forecast DLR some periods ahead is more beneficial in system operation and power flow management [2]. However, forecasting DLR for an entire line is difficult in view of the spatial nature of capacities along the line and the requirement of uncertainty description. To deal with the spatial nature of capacities, a typical approach is to study selected spans with their local weather conditions. Deterministic capacity for each span is calculated and the minimum is then chosen as the rating for the entire line. To handle the uncertainty of the forecasting model, probabilistic DLR with weather uncertainty considered is generated for a single site. Transmission lines are normally designed in line sections consisting of multiple spans. The DLR problem is thus difficult considering the spatial nature of capacities along a transmission line as well as the requirement of uncertainty description. In this paper, a novel probabilistic DLR forecasting method is developed. Capacities at selected spans are first forecast as random variables with means and standard deviations to capture the spatial nature and uncertainties. The line rating for the entire line is then forecasted as a random variable determined as the minimum of span capacities.

Steady-state heat-balance equation is used to calculate line capacity based on the thermal behavior of the overhead transmission line's conductor in *CIGRE* [5] and *IEEE* [6] models. We follow the *IEEE Std* 738 [6] in calculation capacities of selected spans. The heat-balance formula is based on the assumption that in steady state, the sum of heat gains is equal to the sum of heat losses. Heat gains are caused by joule heat from the current (I^2R) and radiation from the sun (q_s), while heat losses are radiation from the conductor (q_r) and convection cooling (q_c) from the wind when it blows the conductor. The equation is expressed by

$$I^2R(T_C) + q_s = q_r(T_C, T_A) + q_c(T_C, T_A, V_s, V_D), \tag{2}$$

where T_C, T_A, V_S and V_D are the line conductor temperature, ambient temperature, wind speed and wind direction, respectively. To estimate the maximum permissible current (I_{max}) under given weather conditions, (3) can be rearranged as

$$I_{\max} = \sqrt{\frac{q_r(T_C^{\max}, T_A) + q_c(T_C^{\max}, T_A, V_s, V_D) - q_s}{R(T_C^{\max})}} \quad (3)$$

where a conductor's max operating temperature ($T_C{}^{max}$) is the maximum temperature allowable to the line.

With the real-time weather, the capacity of selected span is calculated by (4). Since in our method, the ambient temperature, wind speed and wind direction forecasts are random variables with means and standard deviations, capacity of each selected span is forecast as a random variable with mean and standard deviation approximately obtained by Taylor series expansion. The mean capacity of a selected span are approximated by first-order Taylor series expansion:

$$E(I) = E[f(T_A, V_S, V_D)] \approx f[E(T_A), E(V_S), E(V_D)] = f(\mu_{T_A}, \mu_{V_S}, \mu_{V_D}) \quad (4)$$

where $\mu_{T_A}, \mu_{V_S}, \mu_{V_D}$ are the forecast ambient temperature, wind speed and wind direction, respectively. Rating for an entire line is limited by the critical span. The forecast rating is then obtained as the minimum of these random variables:

$$Y = \min_{1 \le i \le n} I_i \quad (5)$$

where I_i is the forecast capacity at span i, Y is the forecast line rating, and n is the number of spans considered.

A 230 kV transmission line [4] between Lookout substation and Plan End power plant in Colorado, United States is adopted for the case study.Four spans (P1, P2, P3 and P4) are selected. Among them, P1, P2 and P4 are in a North-South line direction while P3 is in the West-East direction. Since no measurements of weather sensors installed (if existing) are available, historical weather data are collected from three nearby National Renewable Energy Laboratory weather stations (NREL WS1-3). Figure 3 shows the expected values of forecast capacities for a given case study.

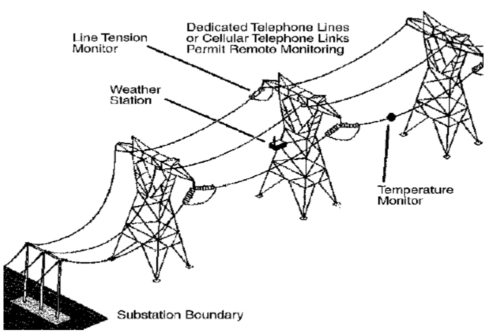

Fig. 2. Measurements for various DLR Determination Methods [3]

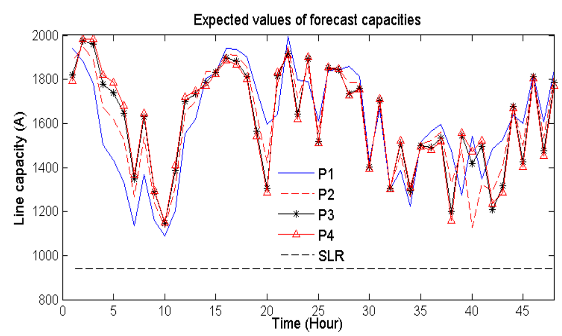

Fig. 3. Capacity forecasted on Oct. 17 and Oct. 18, 2014.

ADAPTIVE TRANSMISSION RATINGS

Adaptive Transmission Ratings (ATR) concept was first introduced in [7] and later on being prototyped [8]. An electrical facility typically has the following emergency thermal characteristics: long-term emergency (LTE), which is 4-h winter or 12-h summer rate; short-term emergency (STE), which is a 15-min rate; and drastic actions load (DAL), which is a 5-min rate [9]. Figure 4 illustrates the definition of the STE and LTE rates as the currents that bring conductor temperature to t_{max} in 15 min and 4 h, respectively, after a step change from initial state I_o. Currently, only DAL, STE and LTE are the three emergency rates practically utilized. However, any point of the rate curve as shown in Figure 5 can be used as an emergency rate. The so-called ATR rate is then the allowed post-contingency current in a conductor if that current can be reduced below LTE within time frame T. The key condition allowing the usage of the STE rate post-contingency in real-time operation is the ability to reduce the load on the overloaded element below LTE level within 15 min after contingency [10]. If it is anticipated that system operable capacity (OC) or dispatchable ramping capability is not sufficient, the LTE rate will be used as a conservative assumption. This can result in expensive underutilization of system transfer capabilities, impose unnecessary constraints and increase electricity production cost. To avoid unnecessary transmission congestion, many times it is up to system operators to use their discretion in 'relaxing' transmission constraints which has significant cost impact and is sometimes controversial.

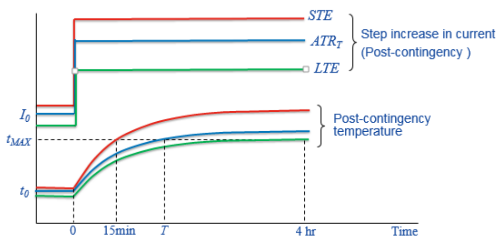

Fig. 4. Change of overhead conductor's temperature at a step change in current.

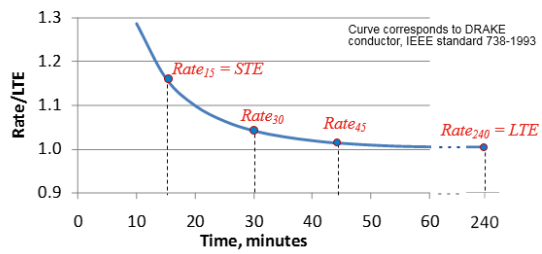

Fig. 5. LTE-normalized emergency rate curve.

For a given power system status, ATR of a conductor can be defined as a maximal post-contingency current in that conductor, which can be reduced below LTE within time T by using available OC. The time frame is a flexible parameter which depends only on the available power system's OC. The key condition for the applicability of the ATR rate defined for a time interval is the ability to reduce the load on the electrical facility from ATR below LTE within the time after contingency. That condition can be satisfied by solving the following equation:

$$Rate(Time) = OC(Time) + LTE \tag{6}$$

where *Rate(Time)* is the physical Rate-Time characteristic of the electrical facility; *OC(Time)* is OC as a function of time determined for the studied electrical facility in post-contingent state by applying dispatchable resources. If appropriate, special protection systems and emergency corrective actions can also be accounted for *OC(Time)* calculation. A solution of (6) gives the ATR and corresponding time interval, which could be thought of as the minimum time needed for OC for the studied electrical facility (Figure 6).

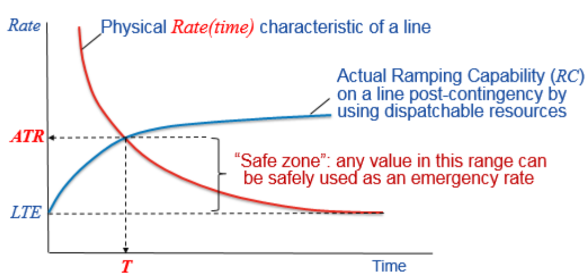

Fig. 6. Illustration of the solution of ATR rate in real-time operation.

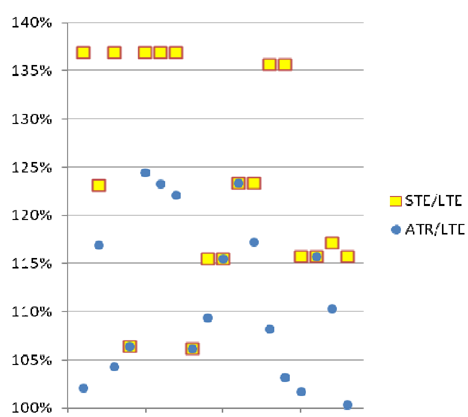

Fig.7. ATR values for certain lines causing RT binding constraints during June – November 2011.

Figure 7 shows results of ATR estimation for transmission lines of interest causing binding constraints in RT during June – November 2011 period at ISO New England. Yellow squares in the graph show the STE/LTE ratio, which the maximal possible value of ATR. Blue circles indicate actual ATR rates as a percentage of LTE. Ratings up to ATR values could be safely enforced in these studied dispatch intervals. For majority of studied cases, ATR values are within 105% - 125% of LTE ratings with an average value of 111.7%. Only one case indicates 100.4% ATR meaning the situation when post-contingency redispatch only cannot help to reduce power flow on lines of interest. All other cases illustrate the availability of significant additional transfer capability of the system not used in current dispatch.

COMBINING DYNAMIC RATINGS WITH ADAPTIVE RATINGS

Dynamic line ratings and adaptive transmission ratings are two different unique concepts and each can more accurately assess the actual rating of a transmission line. DLR and ATR complement each other and can be treated independently. For a given weather condition, we can assess its ATR and for a given time T (15min for STE, 4 hr for LTE), we can assess its DLR(T). In real-time operation, the proposed DLR methodology can be used to determine a real-time rate curve followed by an ATR solution to determine the transient emergency rate. Figure 8 illustrates the transient emergency rating as a two-dimensional function of weather and time.

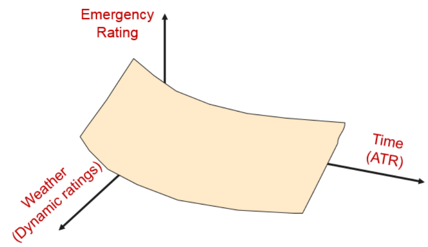

Fig.8. Transient emergency rating as a function of weather and recovery time.

CONCLUSIONS

This paper proposes a comprehensive assessment of transmission ratings by combining the concepts of DLR and ATR for power system and market operations. From our preliminary results, both DLR and ATR offer significant additional transfer capability to existing power systems based on current conservative ratings. As a result, one can conclude that the proposed online assessment of transmission ratings for transmission constraint management can ultimately improve the efficiency of system and market operations. A quantitative assessment of such improvement would be a natural extension of this work.

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