Dynamic Thermal Rating and Allowable Operating Time under Transient Conditions

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Abstract—In electrical systems, one of the main factors that limit the transport of energy is the temperature of the conductor. Knowing the transmission system, and the critical sections both geographical and climatic, the temperature of the line as well as the transient thermal rating can be calculated. A plot of the allowable safe operation time under transient conditions allows increase in transmission capacity without compromising operational security. The estimate of probabilistic thermal risk can afford significant advantage making economic dispatch during favorable conditions without violating the maximum temperature of the transmission lines. This information will be useful in operational decision making and ultimately help to improve the reliability of the power system.

Keywords—Risk Assessment, Cumulants, Moments, Thermal Rating, Probabilistic, Reliability.

I. INTRODUCTION

Increasing consumption of electric energy coupled with financial constraints and environmental restrictions on setting up of new plants has created highly stressed operating conditions and increased vulnerability in networks. This has necessitated the operation of existing systems of transmission close to the limits of their transport capacity without risking the integrity of its physical components, while maintaining reliable operation. Regulations require that the transmission lines must be operated safely at all times. The most significant restrictions on the line are the steady state and transient thermal rating of the conductor. The current carrying capacity of a conductor is limited by the conductor’s maximum design temperature which determines the maximum sag and rate of annealing. High conductor temperatures can cause deeper conductor sag and may result in clearance violations while annealing of the conductors can weaken the conductor and cause its irreversible damage.

Increasing the current carrying capacity of bare overhead conductors has long been of interest to engineers. In [1] a probabilistic method to assess the thermal capacity based on risk is presented. In [2] an approach to assess the cumulative risk associated with overload security for the purpose of midterm power system planning is presented. In [3] authors use the sequential Monte Carlo simulation to assess composite power system reliability and suggest two indices associated with transient stability. An attempt to demonstrate the influence the thermal limits of transmission lines and how these can be exploited for economic generation dispatch is described in [5]. In [6] authors verify through experiments the conductor temperature calculations based on the weather model in [4] and calculate the time to thermal overload. In [7] the authors suggest that a dynamic thermal rating system can be used to upgrade the static rating of existing lines to provide a significant increase of transmission capacity in comparison to the traditional approach.

Historically, transmission lines have had static or fixed ratings that limit the amount of power that can be transferred on the electric grid. Static ratings usually consider a worst case scenario of ambient conditions for calculating the steady state ampacity: high ambient temperature, low wind speed and high solar radiation. The rating is used by the system operator to ensure that the transmission line conductors do not sag below specific limits and come in contact with trees or other objects thus affecting reliability and safety. It was long felt that this rating is conservative and resulted in under-utilization of conductors with increasing energy consumptions and growing financial and environmental restrictions, especially after deregulation. Increase of transmission capacity during favorable ambient conditions would make a significant
difference in economic dispatch of energy over long distances and greater saving in generation cost. Two main approaches have been utilized to overcome this problem of fixed rating; 1) by computation a dynamic thermal rating (DTR) from real time metrological measurements such that the ratings vary as a function of time depending on different ambient conditions and 2) by probabilistic methods. A significant problem associated with DTR however is equipment cost. Moreover, only a particular critical area may be monitored by the equipment adding the possibility of missing important overload problems in other areas not being monitored.

There is a growing interest in using probabilistic methods which account for the stochastic nature of the loads, generation uncertainties, dispatching, outages and ambient conditions. The advantage of the proposed method [8] which uses the cumulants based probabilistic load flow (PLF) approach takes all possible contingencies into account without complex convolutions and provides the densities and distributions of all the bus voltages and line flows in a single run. In order to assess the potential impact of thermal overload it is necessary to obtain a quantitative risk which can indicate the average degree of an overload.

The thermal risk is the probability that the maximum allowable temperature limit of the conductor is exceeded under any ambient condition and can be expressed as,

\[ P(T > T_{\text{max}}) = 1 - \int_{T_{\text{res}}}^{T_{\text{max}}} f(t) \, dt \]  \hspace{1cm} (1)

It is important to note that the risk analysis in the context of overload analysis, involves evaluating the impact or consequences in the event of thermal overload i.e. when line-flow in the conductor exceeds the permissible value. It is however difficult to assess the overload impact in terms of cost as there is no easy way to fix a cost for 110% of maximum rating. Therefore, the impact is considered 1 if violation of performance measures occurs and 0 otherwise.

The paper is organized as follows. Section 2 gives the theoretical background and the proposed method. Section 3 gives a case study using the IEEE RTS 7 Bus test system, while Section 4 gives the concluding remarks.

II. METHODOLOGY

A. Impact of Thermal Overload

Conductor thermal rating under both static (thermal equilibrium) and transient conditions can be evaluated from the heat balance equation of the conductor [4],

\[ Q_s + I^2 R(T_c) - Q_c - Q_r - mC_p \, \frac{dT_c}{dt} = 0 \]  \hspace{1cm} (2)

where \( Q_s \) and \( I^2 R(T_c) \) are the heat gain due to solar radiation and Joule heating due to current flow in conductor (\( R \) is a function of conductor temperature). \( Q_c \) and \( Q_r \) are the heat loss due to convection and long wave radiation. All four heat terms are expressed in W/m. The term \( mC_p \) is the heat capacity of the conductor in J/m°C.

The ampicity (current carrying capacity) of a conductor called the steady state thermal (SST) rating under steady state conditions can be calculated under the assumption that the conductor temperature has already reached equilibrium and the derivative \( \frac{dT_c}{dt} \) is set to zero. Since radiation and convection heat loss rates are not linearly dependent on the conductor temperature, the remaining equation can be solved for conductor temperature in terms of current and weather variables by an iterative process. Under varying current and/or ambient conditions the conductor temperature is calculated as a function of time after the step change of current using equation (2). The equation is solved iteratively at each time step to find the transient thermal rating with respect to a specific time period.

If flow on a line exceeds the maximum allowable conductor temperature (typically, 75°C) that is selected in order to minimize loss of strength, sag, line losses, or a combination of the above, then it can result in one or both of the following:

- Loss of clearance due to sag- In the worst case the line can come in contact with an underlying object, resulting in a permanent fault, loss of life, damage to property and subsequent outage or even cascading events.
- Loss of strength due to annealing- Recrystallization of metal, is a gradual and irreversible process where the grain matrix established by cold rolling is damaged causing loss of strength.

Generally, the safety clearance is specified large enough so that under most conditions the probability of occurrence of flashover is extremely small. However, loss of conductor strength and/or permanent sag increases due to creep elongation of the conductor and accumulates over time. Knowledge of the conductor temperature at different ambient conditions and current flows is important whether it is for the purpose of system planning, or operation and maintenance of transmission lines without compromising on operational security and reliability. Additionally, the monitoring of the temperature in critical stretches of the transmission line, allows forecasting of transmission capacity to the hour and using the favorable periods to make the economic dispatch.

B. Variation in Steady State thermal Rating

Transmission line ratings change continuously depending upon ambient conditions and there are times when transmission line capacity is significantly more than the static transmission rating. Fig 1 shows how the conductor temperature varies from 24°C to 109°C with different ambient conditions when a continuous current (say, SST=733.5 A) flows through the line. The static ratings are specified for “conservative” weather conditions with wind speed of 0.61m/s and summer ambient
The deterministic calculation of thermal rating has at least three major weaknesses. First, probabilities of occurrence of contingencies are ignored which means that even if the consequence of a selected contingency is not very severe, system risk could be high if its probability is relatively high. Second, the uncertainty of load variations, random failures of system components, input data and parameters etc. are not considered. Third, the deterministic approach is based on pre-selected “worst cases” which makes it very inaccurate.

C. Transient Rating and Conductor time to Overload

In case of transient calculations for step change in current while weather conditions remain unchanged it is observed that change in conductor temperature is a function of time. Time taken to reach a steady state value after the change is approximately an hour as the conductor temperature does not rise instantaneously because of its heat capacity, weight and ambient weather conditions. The thermal time constant practically does not vary even for large variations of ambient temperature but depends on wind speed and wind direction. The thermal time constant increases with decreasing speed and for angles of incidence close to 90º. Thus by obtaining the transient behavior of temperature change under different ambient conditions it is possible to know the transient rating of a conductor and the allowable safe operating time before the conductor reaches T<sub>max</sub>.
Table 2: Branch Data for the IEEE RTS 7-Bus System

<table>
<thead>
<tr>
<th>Sl no</th>
<th>Fr-to</th>
<th>Impedance ( Z_{pq} ) (pu)</th>
<th>Ln.ch. adm. B/2 (pu)</th>
<th>Pi</th>
<th>Qi</th>
<th>Rating MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2</td>
<td>0.02 + j 0.06</td>
<td>0.01</td>
<td>0.85</td>
<td>0.15</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>1-3</td>
<td>0.06 + j 0.24</td>
<td>0.02</td>
<td>0.86</td>
<td>0.14</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>2-3</td>
<td>0.04 + j 0.18</td>
<td>0.02</td>
<td>0.95</td>
<td>0.05</td>
<td>130</td>
</tr>
<tr>
<td>4</td>
<td>2-4</td>
<td>0.06 + j 0.18</td>
<td>0.03</td>
<td>0.83</td>
<td>0.17</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>2-5</td>
<td>0.04 + j 0.12</td>
<td>0.02</td>
<td>0.87</td>
<td>0.13</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>2-6</td>
<td>0.03 + j 0.06</td>
<td>0.02</td>
<td>0.93</td>
<td>0.07</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>3-4</td>
<td>0.01 + j 0.03</td>
<td>0.01</td>
<td>0.87</td>
<td>0.13</td>
<td>200</td>
</tr>
<tr>
<td>8</td>
<td>4-5</td>
<td>0.08 + j 0.24</td>
<td>0.06</td>
<td>0.92</td>
<td>0.08</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>6-7</td>
<td>0.04 + j 0.12</td>
<td>0.08</td>
<td>0.89</td>
<td>0.11</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>7-5</td>
<td>0.02 + j 0.06</td>
<td>0.02</td>
<td>0.88</td>
<td>0.12</td>
<td>120</td>
</tr>
</tbody>
</table>

The cumulants are calculated from the moments of each bus voltage and line flows obtained after the process converges with a voltage tolerance of 10^-6. The rearranged Edgeworth series is then used to approximate the PDF and CDF of the bus voltages and line flows. The coefficients of this series are expressed as functions of the Hermite polynomials.

Fig. 4 and 5 shows the PDF and CDF of the 10 different line flows of the RTS 7-Bus Test system. The calculated mean line flows from the PLF are given in Table 3 with their emergency overload ratings.

From the table it is observed that lines 2-4 and 3-4 are prone to overloading with probabilities of 0.5416 and 0.1913. The current flowing in these lines are 111.06A and 276.19A respectively. In case of line 2-4 the overload is 11% more than its rating and at this level for short time emergency loading, the risk will be negligible if ambient conditions do not change greatly as increase of current does not cause the conductor temperature to rise instantaneously because of the heat capacity of the conductor.

For continuous loading however or even for long time emergency loading for say 3 to 4 hours the temperature of the conductor will rise to 76.99ºC and if meanwhile weather conditions become harsher the consequences can become much more severe. In addition, the impact on the system due to outage of this line due to overloading will not be significant as the load on this line can be easily distributed to any of the other lines on either bus 2 or 4 which are loaded below rated capacity.

Considering line 3-4 connected to the load bus 3, the risk associated with this line is quite severe. The lines 1-3, 4-3, 2-3 connected to bus 3 carry a total power of (307.56-j39.91) MVA and provide for the load demand of (300+j50) MVA at bus 3. If line 3-4 fails then in order to compensate for the loss both lines 1-3 and 2-3 will experience increased loads and become overloaded simultaneously. Isolation of bus 3 can result if cascade failure due to overloading occurs.

Fig 6 gives the PDF of the line flow with the percent of overload and Fig 7 gives the PDF of conductor temperature when it carries a continuous current of 276.19A under varying weather conditions. Thus the maximum thermal risk for this current level is 26.4%

Table 3: Comparison of mean flows with their emergency overload ratings

<table>
<thead>
<tr>
<th>line</th>
<th>MVA</th>
<th>MW</th>
<th>MVAR</th>
<th>rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>105.27</td>
<td>101.07</td>
<td>-29.44</td>
<td>2 - 1</td>
</tr>
<tr>
<td>3 - 1</td>
<td>95.17</td>
<td>-68.79</td>
<td>65.77</td>
<td>1 - 3</td>
</tr>
<tr>
<td>2 - 3</td>
<td>126.63</td>
<td>71.79</td>
<td>-104.31</td>
<td>2 - 4</td>
</tr>
<tr>
<td>4 - 2</td>
<td>111.06</td>
<td>-29.89</td>
<td>106.97</td>
<td>2 - 4</td>
</tr>
<tr>
<td>2 - 5</td>
<td>80.66</td>
<td>80.24</td>
<td>-104.31</td>
<td>3 - 2</td>
</tr>
<tr>
<td>2 - 6</td>
<td>38.36</td>
<td>-124.69</td>
<td>100</td>
<td>6 - 2</td>
</tr>
<tr>
<td>3 - 4</td>
<td>293.37</td>
<td>-250.48</td>
<td>200</td>
<td>4 - 3</td>
</tr>
<tr>
<td>3 - 2</td>
<td>161.56</td>
<td>226.13</td>
<td>200</td>
<td>4 - 5</td>
</tr>
<tr>
<td>2 - 7</td>
<td>99.91</td>
<td>-2.32</td>
<td>99.88</td>
<td>4 - 5</td>
</tr>
<tr>
<td>6 - 7</td>
<td>80.76</td>
<td>80.52</td>
<td>-6.25</td>
<td>7 - 6</td>
</tr>
<tr>
<td>7 - 5</td>
<td>59.44</td>
<td>41.59</td>
<td>-42.47</td>
<td>7 - 5</td>
</tr>
</tbody>
</table>

Fig. 4: PDF of line flows using Edgeworth expansion

Fig. 5: CDF of line flows using Edgeworth expansion
Fig 8 plots current changes ranging from 188.3A at maximum rating of 200MVA to 376.6A at 400MVA at fixed ambient conditions of wind speed of 0.61m/s and summer ambient temperature of 40ºC. The time taken by final current to yield the maximum allowable conductor temperature of 75ºC is plotted in Fig 9.

Fig 7: PDF of conductor temperature for current I=276.19A in 3-4 at different ambient conditions

Fig 9: Allowable operating time before conductor reaches 75ºC.

Generally, system operators understand that for a short term condition the thermal limit may be exceeded in emergency situations and as such a period of 10-15 min short time emergency rating is followed. This is observed to go much beyond the actual rating especially taking into consideration sudden drop in wind speed. Therefore, operation on the deterministic STE rating of 10-15 minutes may not ensure the same safety and result in unexpected costs.

IV. CONCLUSION

In many countries the demand for electric power is constantly increasing, and there is a corresponding requirement to increase the power transferred by transmission and distribution lines. A solution would be to build or re-conduct new lines but this may not be feasible on account of economic or environmental considerations. The analysis of the influence of the ambient conditions to determine the actual SST and STE ratings could afford significant advantages. The increased line ampacity and knowledge of time duration with risk involved would be helpful to trade off the benefits and costs in the competitive electricity environment.

REFERENCES
