Scientific Papers of the
Institute of Electrical Power Engineering of the
Wrocław University of Technology

# PRESENT PROBLEMS OF POWER SYSTEM CONTROL

## No 1

Wrocław 2011

*Keywords:*
*dynamic thermal line rating,*
*blackout prevention, heat equation*

Lukasz STASZEWSKI*, Waldemar REBIZANT*

# BLACKOUT PREVENTION POSSIBILITY USING DYNAMIC THERMAL LINE RATING

This paper presents the Dynamic Thermal Line Rating (DTLR) application, based on the heat equations, that makes possible overhead transmission lines operation over their conservatively designed current ratings. The DTLR concept is well known – owing to the CIGRE [1,2] and IEEE [3] standards for overhead bare conductor temperature calculations. However, this phenomenon may not have been used for a purpose of increasing electrical power system stability and thus for blackout prevention. This paper is based on both CIGRE and IEEE standards and presents investigation of the current flow through various conductors. Their temperature and monitoring ambient weather conditions and thermal limits of a conductor are considered. The influence of the weather conditions on the lines flow capacities is presented as a comparison of various types of AFL 6 conductor and various weather conditions. Also the short analysis of the recent blackouts and possibilities of DTLR use are presented. Obtained results are described and conclusions are drawn.

## 1. LINE MONITORING APPROACH

### 1.1. SIGNALS AND VALUES USED FOR CALCULATIONS

The thermal rating, which is also referred to as ampacity, of an overhead line is a maximum value of the current, not causing an excessive sag, exceeding the designed, allowable conductor temperature or loosening strength of a conductor. The sag temperature is a value of temperature for which the smallest legislated clearance between ground and a conductor is met and further heating would endanger public safety. There are many factors influencing temperature of an overhead conductor: current flowing throughout the conductor, wind speed, wind direction in relation to the trans-

---

* Wroclaw University of Technology, Institute of Electrical Power Engineering, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland.

mission line axis, ambient temperature and solar radiation. There are also others factors (e.g. altitude of a line, azimuth of the sun, type of atmosphere, type of ground under the conductor, etc.) but these will not be presented in this paper, despite of being concerned during the analysis, due to a low significance. Since weather conditions are difficult to predict and the public safety must always be ensured, very conservative assumptions must be made when designing transmission lines ampacity. This also applies to the overload protection of transmission lines. The relays settings are chosen to meet the need of switching of the line when the flowing current value is close to the one for which, during the conservatively assumed conditions, the conductor reaches its thermal limit.

The main purpose of the real time monitoring is to utilize overhead lines with their full potential and not only to their limits coming from conservative assumptions. It should be noted that with real time systems, when the external factors are favorable, the line is not operated at temperatures higher than designed but running at its designed temperature for a longer period of time. Thus the line is better utilized.

As the line is running closer to the thermal limit, one can expect the losses to increase. This should be taken into account when optimizing the network configuration and line loading. This paper shows the possibilities of DTLR usage to do so and in addition points at the possibility of using DTLR as a way of blackout prevention in some particular cases.

### 1.2. MATHEMATIC FORMULAE

Conductor temperature calculations according to [3] are based on the heat balance equation (1) and consider heats and losses due to flowing current and various external conditions.

$$q_c + q_r = q_s + q_i \, , \tag{1}$$

where $q_c$ is a cooling due to convection, $q_r$ due to radiation, and $q_s$ and $q_r$ are respectively heating due to solar radiation and due to Joule's law by the current flow.

Cooling due to convection is calculated from two equations (2) and (3), then the higher value is chosen.

$$q_{c1} = \left[ 1.01 + 0.0372 \left( \frac{D \rho_f v_w}{\mu_f} \right)^{0.52} \right] k_f K_{\text{angle}} \left( T_c - T_a \right), \tag{2}$$

$$q_{c2} = \left[ 1.0119 \left( \frac{D\rho_f v_w}{\mu_f} \right)^{0.6} k_f K_{\text{angle}} \left( T_c - T_a \right) \right], \tag{3}$$

where: $\rho_f$ density of air, $v_w$ air stream velocity at a conductor, $k_f$ thermal conductivity of air, $K_{\text{angle}}$ angle between the line axis and wind direction and $T_c$ and $T_a$ conductor and ambient air temperature, respectively.

Cooling due to radiation is usually only a small fraction of total heat balance and is calculated with:

$$q_r = 0.0178 D\varepsilon \left[ \left( \frac{T_s + 273}{100} \right)^4 - \left( \frac{T_a + 273}{100} \right)^4 \right], \tag{4}$$

where: $D$ is external diameter of the conductor, $\varepsilon$ is emissivity.

Heating due to solar radiation is presented by:

$$q_s = \alpha Q_{se} \sin\left(\theta\right) A', \tag{5}$$

where: α is solar absorptivity, $Q_{se}$ is the total solar and sky radiated heat flux elevation corrected, $\theta$ is effective angle of incidence of sun rays and $A'$ is projected area of conductor per unit length.

The last term is heating due to Joule’s law,

$$q_i = I^2 R\left(T_c\right) = I^2 \left( \left[ \frac{R\left(T_{\text{high}}\right) - R\left(T_{\text{low}}\right)}{T_{\text{high}} - T_{\text{low}}} \right] \left(T_c - T_{\text{low}}\right) + R\left(T_{\text{low}}\right) \right), \tag{6}$$

that takes into account not only the flowing current ($I$) but also the change of resistance ($R$) due to conductor temperature and where $R(T_{\text{high}})$, $R(T_{\text{low}})$ are the resistance values for high and low conductor temperatures, respectively.

## 2. CONDUCTOR RATINGS

### 2.1. VARIOUS CONDUCTOR TYPES

Particular conductors differ between each other with the percentage increase of current flow possibilities with use of Dynamic Thermal Line Rating. For this paper purpose the AFL 6 conductor type was chosen in three versions: AFL 6 95, AFL 6 120 and AFL 6 240. The difference between these conductor types is in a cross section surface area (95, 120 and 240 mm$^2$, respectively). In this part of investigation these conductors are put into the tests with the same weather conditions and with different values of current: 110, 115 and 120% of rated current. Rated current value is calculated for the conservative conditions of wind speed 0.1 m/s, ambient air temperature 40°C, and for each conductor. It is a value for which the conductor reaches its thermal limit set to 80°C. The results are presented in Tab. 1, showing the temperatures of the conductors during favorable weather conditions, and in Fig. 1, presenting heating curves for each tested conductor, with respective temperatures that conductor reached for each current value. This illustrates the possibilities of exceeding rated current values while not exceeding thermal limits.

Table 1. AFL 6 conductor temperatures for various current values

| Type of conductor | Rated current [A] | Conductor temperature [$^o$C] | | |
|---|---|---|---|---|
| | | 110% | 115% | 120% |
| AFL 6 95 | 517.1419 | **81.05** | **83.16** | **85.28** |
| AFL 6 120 | 546.1467 | 79.68 | **81.50** | **83.42** |
| AFL 6 240 | 612.8172 | 77.26 | 78.65 | **80.20** |

As it can be seen in above table, the thermal limits exceeding is different for each type of the conductor. And so are the possibilities of controlled overloading them. The best case is for the AFL 6 240 which can be loaded with 115% of the rated current continuously under the favorable weather conditions, and as it can be seen from Fig. 1 with 120% of rated current for about 25 minutes.

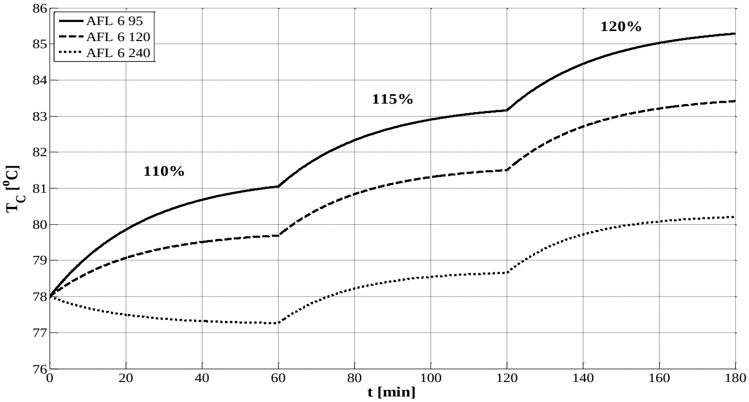

Fig. 1. Temperature of different types of conductors dependent on current values

## 3. BLACKOUT PREVENTION

Large-scale blackouts in North America, Europe, and other countries, such as the 1996 blackout in the U.S. [4], the 2003 blackout in North America [5], the 2003 blackout in Italy [6], and the 2006 blackout in Europe [7], are important reminders of the importance of the reliability of the electric energy infrastructure and the economic impacts of blackouts.

In order to avoid catastrophic outages, appropriate control actions to mitigate emergency conditions including overload conditions in power systems are important. The network problems including overload and voltage problems should be solved with control actions through system operation and/or emergency controls. Among them, overload is an important problem and thus control actions through the collaboration between system operation and emergency controls are vital [8]. One of the parts of the mentioned control of the system operation could be used DTLR technique, for example introducing an additional blocking signal into a protection relay – restraining it from tripping the line when needed.

In general, the sequences of events in the major blackouts followed a common process. Typically, the cascaded events were initiated by a single event or multiple events, such as the 500 kV line outage (U.S. 1996), the generator tripping and the 345 kV line outage (U.S. and Canada 2003), the line outage (Italy 2003) and the coupling operation of bus bars at a substation (Europe 2006). Following the initiating events, the cascaded events took place sequentially. One component failure may trigger another failure, which can bring successive line and/or generator tripping.

There are many causes of cascaded events which contribute to catastrophic outages. They typically include faults, unwanted relay operations (including hidden failures), equipment failures or malfunctions, communication and information failures, and operational errors. Due to the mixture of the causes, prediction of the exact sequence of cascaded events that will take place is practically impossible. However, it is important to look into the fundamental patterns of cascaded events, i.e., which event may trigger other events. Some examples of fundamental patterns of cascaded events are:

- line tripping due to overloading [4, 5, 9, 10],
- generator tripping due to over-excitation [5, 9],
- line tripping due to loss of synchronism [5, 9],
- generator tripping due to abnormal voltage and frequency condition [5,9,10],
- under-frequency/voltage load shedding [4].

From the point of view of this paper, the only one event type taken into account is the first one – line tripping due to overloads. There is a high possibility of DTLR technique usage in that case. Considering mentioned earlier blackouts it is worth pointing some important events.

In case of November 4th, 2006 [11] two important steps of cascade can be distinguished in the whole process. The first was at 22:06, after over 30 minutes since the beginning, when the current on the line Landesbergen-Wherendorf increased from 1800 A to 1900 A within 2 to 3 minutes. Thus, the setting value for protection device (1800 A) – as specified by RWE – was exceeded on this line. And the second, when at 22:10:13, the line Landesbergen-Wherendorf was first tripped by the protection device due to overload. Then two other lines (220 kV and 380 kV) were also tripped due to overloads.

Mentioning blackout in Italy on September 28th, 2003 it is worth to say that as a result of previous events the power deficit in Italy was such that this country started to lose synchronism with the rest of Europe and the lines on the interconnection between France and Italy tripped due to distance relays (first or second step). The same happened for the 220 kV interconnection between Italy and Austria and subsequently, the 380 kV corridor between Italy and Slovenia became overloaded and it tripped too.

The blackouts in the U.S. in 1996 and in North America in 2003 were also analysed and despite that their main causes were not the line overloads, these still remained an important part of blackouts development.

Amongst many other causes and steps of blackout evolution the one, most important from the point of view of Dynamic Thermal Line Rating based on real time lines monitoring, is an overload.

As mentioned in case of Europe 2006 blackout the line overload was 1900 A that is less than 106% of its normal ampacity of 1800 A and the DTLR techniques are capable to dynamically increase the limit up to 120% for a short period of time and up to 115% constantly (Fig. 1). This observation leads to a conclusion, that probably the line could have not been tripped, as a result of the occurring overload. Of course it is difficult to assume that the most favourable situation (weather conditions) was met, at that time, to reach the 120% of the rated ampacity, but it is highly probable that the 106% overload was not a hazard to the line. Thus DTLR application might have been a great relief for the system stress and a way of avoiding further evolution of the failures. The same refers to the Italian blackout in 2003, where also an overload was one of the main causes and the DTLR application might have saved Italian system from extensive failure.

Despite that the U.S. in 1996 and in North America in 2003 blackouts did not show the possibility of DTLR use to direct restrain of failure from spreading wider, they present also the cascaded events pattern ipso facto pointing the overload as a one of possible factors to occur during the whole evolution process.

## 4. SUMMARY

Overloads, even if not as a main cause, still often occur as one of the factors contributing to spreading the power system outage to the wider areas. It creates the need of avoiding them and the Dynamic Thermal Line Rating makes it possible. The analysis carried out and presented above showed that the overload as an excessive current flow can be sometimes allowed. It depends on the transmission line ambient weather conditions. For favourable conditions: high wind speeds, low air temperature, etc. it is possible to provide from a few to even a few tens of minutes of an additional time to restrain standard protection from operation and to maintain the power system integrity.

## REFERENCES

[1] *Mathematical model for evaluation of conductor temperature in the steady (or quasi-steady) state (normal operation),* CIGRE, ELECTRA No. 144 Oct. 1992, 109-115.

[2] *The thermal behavior of overhead conductors,* CIGRE, ELECTRA No. 174 Oct. 1997, 59-69.

[3] *IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors*, IEEE Std 738-2006 (Revision of IEEE Std 738-1993).

[4] WSCC, *Western Systems Coordinating Council (WSCC) Disturbance Report for the Power System Outage that Occurred on the Western Interconnection, August 10, 1996,* approved by the WSCC Operations Committee on October 18, 1996.

[5] U.S.-Canada Power System Outage Task Force, *Final Report on the August 14th blackout in the United States and Canada*, United States Department of Energy and National Resources Canada, April 2004.

[6] UCTE, *Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy*, April 2004.

[7] UCTE, *Final Report on the Disturbances of 4 November 2006,* Jan. 2007.

[8] YAMASHITA K., LI J., ZHANG P., LIU C-C, *Analysis and Control of Major Blackout Events*, Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES

[9] BIALEK J. *Why has it happened again? Comparison between the UCTE blackout in 2006 and the blackouts of 2003*, IEEE, PowerTech 2007, Paper ID: 177

[10] ANDERSSON G., DONALEK P., FARMER R., HATZIARGYRIOU N., KAMWA I., KUNDUR P., MARTINS N., PASERBA J., POURBEIK P., SANCHEZ-GASCA J., SCHULZ R., STANKOVIC A., TAYLOR C., and VITTAL V., *Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic Performance,* IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 4, NOVEMBER 2005.

[11] CHUNYAN Li, YUANZHANG Sun, XIANGYI Chen, *Analysis of the Blackout in Europe on November 4, 2006,* The 8th International Power Engineering Conference (IPEC 2007), 939-944.

## ZASTOSOWANIE DYNAMICZNEJ CIEPLNEJ OBCIĄŻALNOŚCI LINII PRZESYŁOWYCH JAKO MOŻLIWOŚCI ZAPOBIEGANIA BLACKOUTOM

Artykuł przedstawia zastosowanie dynamicznej termicznej obciążalności linii przesyłowych (DTOLP) jako narzędzia umożliwiającego unikanie powstawania lub dalszego rozwoju powstałej już

awarii wielkoobszarowej systemu elektroenergetycznego. Sama idea DTOLP jest dobrze znana, dzięki standardom CIGRE i IEEE służącym do obliczeń termicznego stanu przewodu jako funkcji warunków pogodowych oraz przepływającego przez przewód prądu elektrycznego. Na potrzeby artykułu korzystano z obu standardów i zaprezentowano analizę wpływu przepływu prądu w różnych przewodach na ich możliwości przesyłowe w zależności od otaczających je warunków pogodowych. Dodatkowo artykuł podkreśla istotność przeciążeń linii przesyłowych, jako elementu wywołującego lub pogłębiającego awarie wielkoobszarowe oraz możliwość zastosowania dynamicznej termicznej obciążalności linii przesyłowych w celu zapobiegania tym zjawiskom.