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Dynamic Line Rating - Technologies and Challenges of PMU on Overhead Lines: A Survey

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***Abstract*—This article reviews direct and indirect methods developed for dynamic line rating on overhead lines, and their applications (reduction of bottlenecks, congestion costs, load shedding, among others) in the operation and control of power systems as smart grid technology. Besides, four elements for line rating computation and monitoring are identified, these are: sensors, communications, management information system and information analysis tools, which are part of integral dynamic line rating systems. Finally, the benefits and challenges of using phasor measurement units for real time capacity estimation on overhead lines are analyzed, highlighting the impact of weather changes along the entire line.**

***Index Terms*—Dynamic Line Rating *(DLR)*, Overhead Line *(OHL)*, Phasor Measurement Units *(PMU)*, Smart grids**

I. Introduction

With the advent of information technologies, smart grids and Phasor Measurement Units *(PMU)* in the electric systems the evolution of *SCADA* system is a reality, allowing monitoring, control, assessment, diagnose and analyze energy systems in real-time.

In spite of these developments, the new dynamic of electric systems as result of the penetration of renewable energy, electric vehicles, energy storage, demand management, among other things, has resulted in network assets (including Overhead lines-*OHL*) operating close to the maximum operation limits, including thermal capacity. In the operation of power systems two thermal limits for *OHL* have been defined, the first one is related to transient state, it is used for short overloads or contingencies that might occur during system operating and it is defined by a relationship between maximum current and time. The second limit is used for steady state conditions and it restricts the maximum current intensity flow through the conductor for an indefinite period of time. These two limits depend on weather, current intensity, mechanical and thermal properties of the conductor and the geometric characteristics along the *OHL*. These thermal restrictions have to be considered in the operation and control of power systems, for contingency management, safe and economical operation, maintenance and expansion plans, as shown in Figure 1. These thermal limits have been commonly fixed based on worst weather conditions (called *static line rating -SLR*), with the aim of guarantee high system reliability through the *OHL* lifecycle.

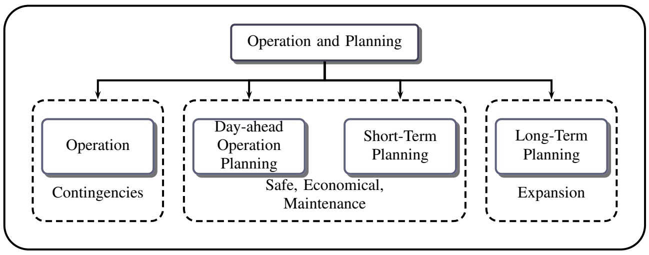

Figure 1. *DLR* Applications in the operation and control of power systems

In order to push *OHL* capacity limits, four asset renewal techniques are proposed: uprating, upgrading, refurbishment and expansion [1]. Within uprating solutions is dynamic line rating (*DLR*), which has the advantages of low investments, null environmental impact and fast implementation. For instance, in [2] it is reported that the cost of implementing a *DLR* system is quickly compensated by the savings of reducing congestion, when wind generators penetrated the grid. *DLR* technology also known as *Real Time Thermal Rating RTTR* establishes dynamic limits to *OHL* according to weather variations, and it is considered as a solution to the challenges facing the operation and control of power systems (Figure 1), as result of congestion, bottlenecks and the need for high reliability levels, for existents and future energy systems [3], [4], since *DLR* has the ability to optimize the conductor ampacity through real time information analysis based on weather conditions. In [5], [6], [7] an increase of $10-30\%$ is reported in *OHL* capacity when *DLR* is used, especially where high renewable energy sources have been included to generation.

The first *DLR* applications were based on estimations of historical climate reports from weather stations [5]. With these estimations the line rating was fixed for different seasons and hours throughout the year. With the passing of time, different and novel *DLR* technologies have been developed seeking improving *OHL*, pushing its stable and transient thermal limits during the operation states of power systems, as shown in Figure 2.

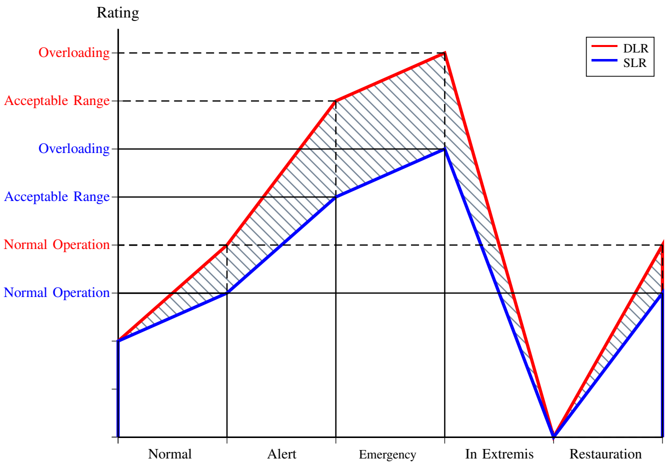

Figure 2. Influence of *DLR* in operating states of power systems

Some surveys about DLR had been presented. The first *DLR* state of the art summited [8] summarized the technologies for calculating *DLR*. Afterwards, in [9] a review and evaluation of direct technologies for *DLR* is presented. In [10], it is made a review of *DLR* for wind power integration. Finally, in [11] a survey about forecasting for *DLR* is undertaken. Seeing that, in this article a review of application of *DLR* in power systems is carried out, moreover, the main elements of a *DLR* system are identified and the challenges of *PMU* as *DLR* method are addressed. This paper is organized as follow, in section II the background of *DLR* on *OHL* is presented. Section III described the different methods used to calculate line capacity. Section IV summarizes the application of *DLR* on power systems and smart grids, and identify the elements to implement this technology. Finally, section V analyzes the use and challenges that face *PMU* for *DLR*, emphasizing on weather changes along *OHL*.

II. Background

Dynamic rating methods have been applied to transformers, cables, *OHL* and terminal equipment [12] with the aim of optimizing the economic dispatching, reliability and future investments. *OHL* conductors have high thermal constants [6], and thus, these elements reach their thermal limits faster. Besides, *OHL* are more exposed to weather changes. For these reasons, *DLR* has been focused and applied mainly to *OHLs*, because it is the first element that limits the power transmission when weather or operating conditions change.

Maximum power transfer in transmission lines is fixed based on the next three limits: stability, thermal and mechanical. The stability limit commonly restricts the maximum power for high voltage and long lines and it depends on the line impedance. The thermal limit is a constrain that refers to the loss of thermal and mechanical properties as result of overheating. Finally, the mechanical limit applies for *OHL* and it is defined by the minimum distance between conductor and ground; this usually limits the current intensity for short and medium *OHL* [13]. For instance, in studies carried out in Korean transmission systems [14], the capacity in *OHL* is defined by the temperature that exceed the mechanical limit and not the thermal limit (loss of mechanical and thermal properties).

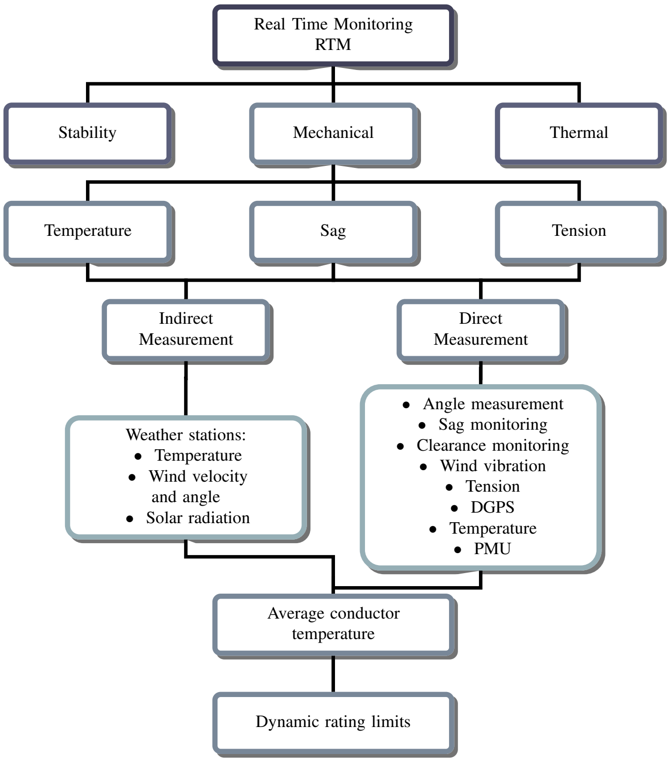

Figure 3. DLR on OHL, - estimation methodologies, based on [18]

Different technologies have been developed in the last years with the objective of measure weather and mechanical variables, required for accurate *DLR* [15]. With these developments line ratings have been increased.

OHLs change its mechanical parameters as a result of weather and current intensity variations. This behavior is reflected in the increase or decrease of line length, altering the distances to ground in each span, putting at risk the system and the elements that are locate around, if the maximum sag is exceed. In fact, just one span can limit the *OHL* rating and this is defined commonly as critical span. For online monitoring this critical span different devices and technologies are available [7], [16], [17].

Figure 3 shows the estimation methodologies for *DLR* on *OHL* proposed by CIGRE [18] when the capacity is limited by conductor elongation (mechanical limit). This procedure includes technologies (directs and indirect) used for computing the average conductor temperature. United Kingdom and USA have developed methodologies for establishing the conductor operating temperature based on weather measurements obtained from weather stations nearby to *OHL* [19].

For implementing *DLR* systems is necessary to determine the optimal number and location of monitoring devices, this is defined based on line design, climate statistics and weather models, with the aim of identifying critical spans along the

OHL [20], increasing the system capacity and reliability. Reference [21] shows that increasing on the number of weather stations can decrease the system reliability given the large number of measurements errors, requiring using error minimization techniques.

III. Conductor Temperature Calculation

The capacity on *OHL* is determined for the maximum temperature inside the conductor and the maximum sag that can put at risk the system. The temperature depends on the current intensity and the ability of the conductor to transfer heat to the environment, as result of energy balance process. This heat transfer phenomenon depends of the conductor characteristics, the weather and the dynamic behavior of the load. Thus, for computing *OHL* capacity two measurement methods are used [5], [18], the first one is defined as indirect method and it is based on measurement from weather stations nearby to the line or in climate reports. The second method is called direct and it is based on measurements of mechanical tension (H), conductor temperature (T_S) or sag (D) (Figure 3).

A. Indirect Methods

CIGRE and *IEEE* [22], [23] have developed analytical methodologies and standards for computing conductor temperature in stable and transient state, based on the weather and heat balance equations. For estimating this temperature, it is necessary to know some weather variables (ambient temperature T_a, wind speed and direction $\vec{\vartheta}$, and solar radiation S), conductor characteristics and current intensity (i). All these variables are related through heat transfer equations. Alternatively, Finite Element Method can be used with the aim of calculating the thermal rating of *OHL* [24] and cables [25], taking into account load variations. For this methodology it is necessary more computational resources that analytical methods and the previous knowing of convection and radiation coefficients of the line or cable.

Reference [2] analyses the influence of different weather variables on *OHL* rating, additionally, it is carry out a sensitivity analysis, which concluded that wind speed and direction has the highest impact on line current capacity. In [26] finite arithmetic method for minimizing errors in rating estimation is applied, having into account the high variation in the uncertainty of the measurements and in the heat transfer model. In [27] the temperature error over *OHL* rating based on heat transfer models is analyzed and it is determined that for low wind speed, high radiation levels, low current intensities and high ambient temperatures the error in the estimation of rating is higher.

B. Direct Methods

Different technologies are used as direct methods for *DLR*. The first one involved temperature sensors over conductors of *OHL* [5], thereafter, different devices for direct measurement of mechanical and thermal variables were developed [18]. These methods computing online the average conductor temperature of a line section or span (commonly a critical span) without needing of knowing weather variables or current intensity. Direct methods have more precision compared with indirect methods. However, recent years have seen a tendency to used hybrid measurements [28] (direct and indirect) with the aim of improve the reliability of online *OHL* rating estimation. The advantage of the hybrid method is that it gets accurate results for the entire *OHL* at low costs, without using direct measurements in all spans (just in critical sags).

Reference [28] analysis the different direct methods for *DLR*, where the advantages and disadvantages of each method are addressed through calculation of standard deviations in the computing of line capacity, concluding that the method that has the best performance is which measured directly *OHL* sag (D).

IV. *DLR* in Power Systems Analysis and Smart Grids

DLR is used in power systems analysis as smart grid technology, it seeks to optimize the system, increasing reliability, and on-line rating monitoring using information technologies.

A. Power Systems

The economic dispatch can be changed using *DLR* on *OHL*, with the aim of reducing losses and/or generation costs. In [6] a *DC* load flow algorithm is implemented seeking optimizing the distributed generation, resulting in improvements when *DLR* is compared with *SLR*; this algorithm was tested in different operation scenarios. In [29] a similar analysis was made, concluding that for the German power system, it is not necessary to reduce generation or load shedding because of line congestion when renewable sources are integrated, if *DLR* is used; this study was based on weather forecast and historic load profiles.

In [21] a Markov model for a transmission system including *DLR* is presented. The annual variation of *DLR* limits is represented by means of fuzzy equivalent, with the aim of accounting the failure rate and the repair time of *DLR* measuring devices. This model is tested on a power system and it seeks to analyze its reliability when load shedding is optimized. The optimization is done with DC load flows. A load shedding strategy for power systems is presented in [30], considering *DLR* limits. This strategy consists in analyzing the congestion in a power system, considering a multi-objective problem, where the objective functions are the minimization of load shedding and the maximization of reliability. The load flows are solved using Newton Raphson method. In [31] the uncertainty product of error in weather forecast models for *DLR* are analyzed, with the purpose of compute the amount and location of power that must be re-dispatched. Within this analysis a reduction in operation costs was achieved. In summary, system optimization is possible when *DLR* is implemented, because line capability constrains due to mechanical limit are commonly increased.

B. Integrated DLR Systems, a Smart Grid Application

The integrated *DLR* systems (*iDLRS*) have the main characteristic of measure a set of weather and/or mechanical variables, in order to compute *OHL* rating. This new limit is sent and storage in *SCADA* system. Thus, system operators can take this information and analyze it, seeking to optimize the lines capacity and modifying the load flows.

Due to the befits of including *iDLRS* in the operation of the system, different technologies have emerged. In [3] is analyzed *Distributed Temperature System (DTS)*, which is used for online temperature monitoring in different sections of a transmission cable. The temperature is measured with optic fiber located along the conductor. With these measurements is estimated the cable capacity based on hot spots, allowing the implementation of an *iDLRS*.

In [32] a hybrid model called *Tension and Ampacity Monitoring System (TAM)* is presented. This model estimates the wind speed, conductor temperature and line rating, from measurements of mechanical tension, ambient temperature, solar radiation and current intensity. Additionally, *TAM* estimates the conductor fatigue thought a self-calibration process between mechanical tension and conductor temperature, since, this fatigue influences the *OHL* capacity. Finally, *TAM* system allows to compute *DLR* having into account the conductor fatigue.

iDLRS systems are composed of different layers. For *RTTR* in underground transmission cables four elements have been defined [3]: sensors, measurement devices, software for data analysis and *SCADA* system to integrate the information. Based on cable *DLR* systems and technologies developed, for *OHL* can be identified the next layers: sensing and measuring, communications, management information system and analysis and optimization. To illustrate, Figure 4 shows the layers of *iDLRS* for *OHL* within a grid.

V. *PMU* FOR DYNAMIC LINE RATING

Among the multiples applications of *PMU* in the operation, control and monitoring or power systems is *DLR*. This device has the advantages of providing an overview of conductor temperature (T_S), and to have an existing infrastructure capable to guarantee the functioning and reliability of an *iDLRS* at low cost, due to have the four layers defined in the previous chapter. For implementing this technology is necessary to estimate the electrical parameters of *OHL*, from voltage (v) and current (i) measurements. Afterward, this information must be sent to *SCADA* or EMS (Energy Management System).

DLR by means of *PMU* is based on the change of electrical parameters (Resistance *R* and capacitance *C*) as result of weather variations. From *R*, the average conductor temperature can be computed, because in electrical conductors the resistance change with frequency, average current density and temperature [22]. For *DLR* applications the frequency is constant, the current density depends of conductor characteristics and the load flow, and finally, the temperature depends on conductor losses and weather conditions. The capacitance method considers the relation between *C* and sag, due to the influence of ground clearances in the distribution of electrical field. In [33], it is used the average sag, computed from the capacitance and resistance for calculating line rating; alternatively, in [34]

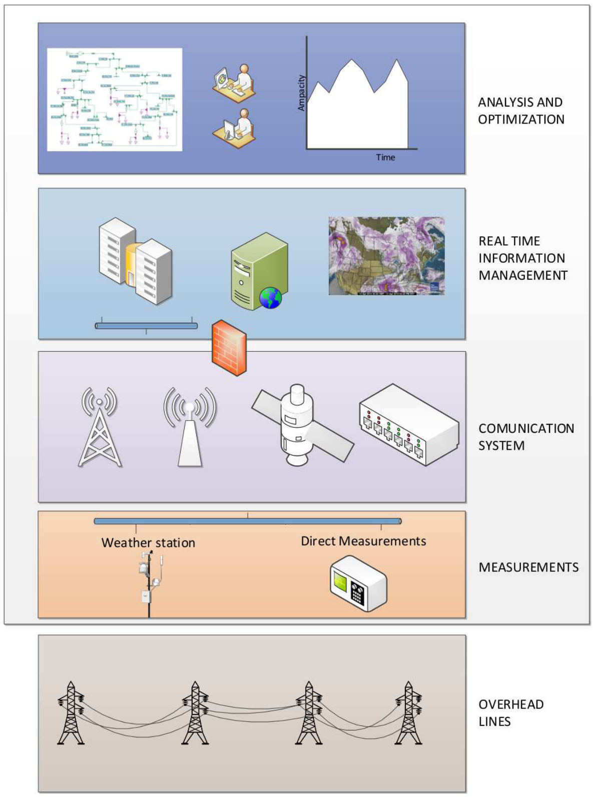

Figure 4. *iDLRS* layers for *OHL*

the sag is calculated from resistance. Because of the nature of measurements errors, which are propagated due to the measures are indirect, estimation techniques have been applied for *DLR* when PMU measurements are used, with the aim of minimize the error, using distributed [35] and π [36] line models.

Figure 5 shows an overview of *DLR* based on π line model estimated from *PMU*, where R, L, C parameters change in function of the average temperature (T_S), line length (ℓ) and sag (D). The measurements for estimating conductor rating are (v) and (i) in each line end. This method faces challenges when weather conditions (T_a,$\vec{\vartheta}$,S) fluctuate along the line and/or the OHL has multiple conductors with different resistivities, considering that *R* and *C* parameters only compute the average temperature along the line. In [37], *PMU* application for *DLR* is compared with other methods, where average temperature is estimated along *OHL*; this temperature varied on average 5°C compared with temperatures measured on hot spots (commonly critical spans). In [38] the weather variations along *OHL* are having into account when *PMU* is used, estimating the resistances for each line section from weather, and therefore, the conductor temperature. Finally, the sum of all resistances is forced to be equal to the resistance estimated from *PMU*.

Given that, the coldest and warmest line sections, or true temperature in critical spans cannot identify when only *PMU* measurements are used. Thus, this method can put at risk

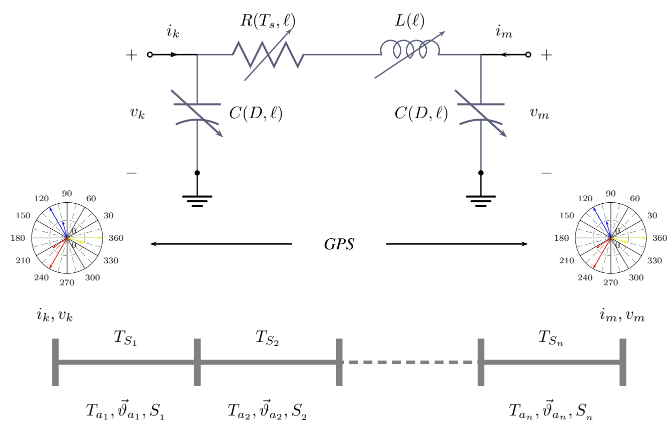

Figure 5. Overview of *PMU* method for *DLR*

the system. To meet this challenge and take advantage of *PMU* infrastructure, it is necessary combined *PMU* measures with other direct or indirect measurements. An option is to combine *PMU* method with weather reports and forecasting. Actually, models with resolutions of the order of 1 km are available for using in *DLR* [11]. This resolution is enough for the majority of distances between tensioning towers or ruling spans. However, the use of weather models included high errors in the computing of variables comparing with *PMU* measurements errors. For this reason, it is recommended to apply error minimizing techniques and to develop algorithms for estimating the conductor temperature in each line span for thermal steady and unsteady state.

VI. Conclusions

DLR has increased its use because it allows optimizing and increasing the reliability of *OHL*, in the operation and control of power systems, reducing costs related to *OHL* congestion, bottlenecks, future investments and environmental impacts.

In this article was identified four main elements for *iDLRS* in available technologies. By mean of these elements, online *OHL* rating monitoring is possible, achieving improvements in the operation and control of power systems.

From knowledge of *R* and *C* parameters is possible to compute the average span and average conductor temperature of the entire line using *PMU*, as long as, the weather conditions don't change along the conductor, this rarely occurs. For this reason, models that take into account the monitoring of critical spans or line sections with unfavorable weather conditions joint with *PMU* are necessary, using state estimation techniques, seeking minimize errors in the different measurements, thus, increasing the reliability of the system.

References

[1] C. international des grands reseaux electriques. Comite d'etudes B2, *Guidelines for Increased Utilization of Existing Overhead Transmission Lines*. CIGRE, 2008.

[2] M. Simms and L. Meegahapola, "Comparative analysis of dynamic line rating models and feasibility to minimise energy losses in wind rich power networks," *Energy Conversion and Management*, vol. 75, no. 0, pp. 11–20, 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0196890413002999

[3] G. Migliavacca, *Advanced Technologies for Future Transmission Grids*, ser. Power Systems. Springer, 2012.

[4] W. Winter, K. Elkington, G. Bareux, and J. Kostevc, "Pushing the Limits: Europe's New Grid: Innovative Tools to Combat Transmission Bottlenecks and Reduced Inertia," *Power and Energy Magazine, IEEE*, vol. 13, no. 1, pp. 60–74, jan 2015.

[5] S. D. Foss and R. A. Maraio, "Dynamic line rating in the operating environment," *Power Delivery, IEEE Transactions on*, vol. 5, no. 2, pp. 1095–1105, 1990.

[6] M. Z. Degefa, M. Humayun, A. Safdarian, M. Koivisto, R. J. Millar, and M. Lehtonen, "Unlocking distribution network capacity through real-time thermal rating for high penetration of DGs," *Electric Power Systems Research*, vol. 117, no. 0, pp. 36–46, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779614002879

[7] Y. Yang, R. G. Harley, D. Divan, and T. G. Habetler, "Thermal modeling and real time overload capacity prediction of overhead power lines," in *2009 IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives*. IEEE, aug 2009, pp. 1–7. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5292772

[8] B. S. Howington and G. J. Ramon, "Dynamic Thermal Line Rating Summary and Status of the State-of-the-Art Technology," *Power Delivery, IEEE Transactions on*, vol. 2, no. 3, pp. 851–858, 1987.

[9] S. C. E. Jupe, M. Bartlett, and K. Jackson, "Dynamic thermal ratings: the state of the art."

[10] E. Fernandez, I. Albizu, M. Bedialauneta, A. Mazon, and P. Leite, "Review of dynamic line rating systems for wind power integration," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 80–92, jan 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032115007960

[11] A. Michiorri, H.-M. Nguyen, S. Alessandrini, J. B. Bremnes, S. Dierer, E. Ferrero, B.-E. Nygaard, P. Pinson, N. Thomaidis, and S. Uski, "Forecasting for dynamic line rating," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1713–1730, dec 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032115007819

[12] R. Adapa and D. A. Douglass, "Dynamic thermal ratings: monitors and calculation methods," in *Proceedings of the Inaugural IEEE PES 2005 Conference and Exposition in Africa*. IEEE, 2005, pp. 163–167. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1611807

[13] K. O. Papailiou, *Overhead Lines: A Cigre Green Book*. Cigre, 2014.

[14] S. D. Kim and M. M. Morcos, "An Application of Dynamic Thermal Line Rating Control System to Up-Rate the Ampacity of Overhead Transmission Lines," *Power Delivery, IEEE Transactions on*, vol. 28, no. 2, pp. 1231–1232, 2013.

[15] J. Fu, D. J. Morrow, and S. M. Abdelkader, "Modelling and prediction techniques for dynamic overhead line rating," in *Power and Energy Society General Meeting, 2012 IEEE*, 2012, pp. 1–7.

[16] S. M. Mahajan and U. M. Singareddy, "A Real-Time Conductor Sag Measurement System Using a Differential GPS," *Power Delivery, IEEE Transactions on*, vol. 27, no. 2, pp. 475–480, 2012.

[17] J. Johnson, C. Smith, M. Young, K. Donohoo, R. Owen, E. Clark, R. Espejo, S. Aivaliotis, R. Stelmak, R. Mohr, E. Al., and E. al., *Dynamic Line Rating Oncor Electric Delivery Smart Grid Program*, may 2013. [Online]. Available: http://www.osti.gov/scitech/servlets/purl/1111102

[18] S. Rob, L. Jean-Louis, S. Tap, D. Dale, L. Mark, B. Gerhard, P. R. Watt George, F. Patrick, and S. Michael, *Guide for Application of Direct Real-time Monitoring Systems*. Paris: CIGRE, 2012.

[19] D. M. Greenwood, J. P. Gentle, K. S. Myers, P. J. Davison, I. J. West, J. W. Bush, G. L. Ingram, and M. C. M. Troffaes, "A Comparison of Real-Time Thermal Rating Systems in the U.S. and the U.K." *Power Delivery, IEEE Transactions on*, vol. 29, no. 4, pp. 1849–1858, 2014.

[20] M. Matus, D. Saez, M. Favley, C. Suazo-Martinez, J. Moya, G. Jimenez-Estevez, R. Palma-Behnke, G. Olguin, and P. Jorquera, "Identification of Critical Spans for Monitoring Systems in Dynamic Thermal Rating," *Power Delivery, IEEE Transactions on*, vol. 27, no. 2, pp. 1002–1009, 2012.

[21] H. Shaker, H. Zareipour, and M. Fotuhi-Firuzabad, "Reliability Modeling of Dynamic Thermal Rating," *Power Delivery, IEEE Transactions on*, vol. 28, no. 3, pp. 1600–1609, 2013.

[22] "IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors," *IEEE Std 738-2006 (Revision of IEEE Std 738-1993)*, pp. c1–59, 2007.

[23] R. Stephen, D. Douglas, G. Mirosevic, H. Argasinska, K. Bakic, S. Hoffman, J. Iglesias, F. Jakl, J. Katoh, T. Kikuta, and Others, *Thermal behaviour of overhead conductors*. CIGRE, 2002.

[24] F. Á. Gómez, J. M. G. de Maria, D. G. Puertas, A. Baïri, and R. G. Arrabé, "Numerical study of the thermal behaviour of bare overhead conductors in electrical power lines," in *RECENT RESEARCHES in COMMUNICATIONS, ELECTRICAL & COMPUTER ENGINEERING*. Playa Meloneras, Gran Ca naria, Canary Islands: WSEAS Press, 2011, pp. 149–153.

[25] J. Nahman and M. Tanaskovic, "Determination of the current carrying capacity of cables using the finite element method," *Electric Power Systems Research*, vol. 61, no. 2, pp. 109–117, 2002. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779602000032

[26] A. Piccolo, A. Vaccaro, and D. Villacci, "Thermal rating assessment of overhead lines by Affine Arithmetic," *Electric Power Systems Research*, vol. 71, no. 3, pp. 275–283, 2004. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779604000677

[27] I. Albizu, E. Fernaandez, A. J. Mazoon, and J. Bengoechea, "Influence of the conductor temperature error on the overhead line ampacity monitoring systems," *Generation, Transmission Distribution, IET*, vol. 5, no. 4, pp. 440–447, 2011.

[28] W. A. C. Clifton R. Black, "Key Considerations for the Selection of Dynamic Thermal Line Rating Systems," *Power Delivery, IEEE Transactions on*, vol. PP, no. 99, p. 1, 2014.

[29] B. Xu, A. Ulbig, and G. Andersson, "Impacts of dynamic line rating on power dispatch performance and grid integration of renewable energy sources," in *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES*, oct 2013, pp. 1–5.

[30] W.-Q. Sun, Y. Zhang, C.-M. Wang, and P. Song, "Flexible load shedding strategy considering real-time dynamic thermal line rating," *Generation, Transmission Distribution, IET*, vol. 7, no. 2, pp. 130–137, feb 2013.

[31] M. A. Bucher and G. Andersson, "Robust Corrective Control Measures in Power Systems With Dynamic Line Rating," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2034–2043, may 2016. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7163367

[32] I. Albizu, E. Fernandez, P. Eguia, E. Torres, and A. J. Mazon, "Tension and Ampacity Monitoring System for Overhead Lines," *Power Delivery, IEEE Transactions on*, vol. 28, no. 1, pp. 3–10, 2013.

[33] S. R. Jiliusson, "Using PMU Measurements to Assess Dynamic Line Rating of Transmission Lines," M.Sc. Thesis in Electrical Power Systems and High Voltage Engineering, Aalborg University, 2013.

[34] I. Oleinikova, A. Mutule, and M. Putnins, "PMU measurements application for transmission line temperature and sag estimation algorithm development," in *Power and Electrical Engineering of Riga Technical University (RTUCON), 2014 55th International Scientific Conference on*, oct 2014, pp. 181–185.

[35] Y. Du and Y. Liao, "On-line estimation of transmission line parameters, temperature and sag using PMU measurements," *Electric Power Systems Research*, vol. 93, pp. 39–45, dec 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779612002076

[36] S. S. Mousavi-seyedi, F. Aminifar, S. Azimi, and Z. Garoosi, "On-line assessment of transmission line thermal rating using PMU data," in *2014 Smart Grid Conference (SGC)*. IEEE, dec 2014, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=7090880

[37] M. Weibel, W. Sattinger, P. Rothermann, U. Steinegger, M. Zima, and G. Biedenbach, "Overhead line temperature monitoring pilot project," *CIGRE 2006 Session*, 2006.

[38] C. Rehtanz, "Synchrophasor based thermal overhead line monitoring considering line spans and thermal transients," *IET Generation, Transmission & Distribution*, vol. 10, no. 5, pp. 1232–1239(7), apr 2016. [Online]. Available: http://digital-library.theiet.org/content/journals/10.1049/iet-gtd.2015.0852