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Impact of Thermal Uprating and Emergency Loading of OHL Networks on Interconnection Flexibility

K. Kopsidas
School of Electrical and Electronic Engineering
University of Manchester
Manchester, UK

***Abstract*—This paper assesses the impact of flexible thermal uprating methods and the utilization of the emergency loading capability of overhead line (OHL) networks on network transmission adequacy and flexibility. It implements an electro-thermal modelling of OHLs within a network reliability evaluation analysis to capture the risk of ageing during the operation and then performs a cost/worth analysis of the value that extensive emergency loadings could have on the network performance. The results indicate that increased emergency rating durations could increase network flexibility for operators during unexpected events, however, on the cost of increased ageing. Time varying line rating (TVLR) is the most optimum solution as it provides increased flexibility without increasing the risk of conductor ageing.**

Keywords—adequacy, interconnection flexibility, electro-thermal modelling, overhead line ageing, line rating, transmission, reliability.

I. INTRODUCTION

Increasing pressure for networks to provide additional connection of generation from remote areas and increased demand from transportation and heat can lead to constraints in transmission power network and interconnection adequacy and requirements for expensive reinforcements. Some of these might be very difficult to implement also due to additional public opposition resulting in delays on new connection of renewable energy resources (RES).

The financial and social constraints of new power network reinforcements led utilities towards alternative methods of improving network flexibility and reliability. These methods solely aim to address the challenges involved in increasing the utilization of existing networks by removing voltage and thermal constraints through the existing infrastructure. Consequently, flexible alternative current transmission system (FACTS) devices have been installed at strategic positions within the network that can justify their costs through increased number of operation providing active power flow control during normal and N-1 contingency operation [1, 2]. FACTS devices are also used to address challenges in connecting wind-farms when increased level of wind power is injected in the network [3, 4]. Furthermore, the implementation of FACTS devices is currently considered for reinforcing distribution networks and challenges introduced by distributed generation and RES connection at lower voltage networks with increased losses and week connection [4-6].

There are occasions, however, when the power flow reinforcement could be achieved in a simpler and cheaper way by increasing the thermal rating of the overhead lines (OHLs), especially when they were initially rated conservatively at low operating temperatures. Such inexpensive methods can increase the adequacy of conservatively rated lines by "hot wiring"; that is, the decision of a utility to operate the lines at operating temperatures higher than those of their initial designs [7]. There are several methods with which increased power rating through "hot wiring" can be achieved, such as re-evaluating the OHL design for conservatively rated lines or advancing the thermal rating method used to perform the initial calculations. Therefore, implementing different rating models, such as seasonal line rating (SeLR), probabilistic line rating (PLR) or time varying line rating (TVLR) [8-14] can result in increasing the power transfer capabilities of the same OHL with no additional cost. When PLR OHL modeling is implemented to increase power delivery of the same OHL, then an increased risk of overheating the conductor is considered in the design. This method is probabilistic in nature and therefore based on a risk of exceeding a specific static line rating value. Consequently, PLR includes some increased risk of exceeding the designed conductor temperature compared to the one expected under static line rating (SLR) design. This is considered in the design and depends on the utility's risk acceptance level which determines the expected improvement of the PLR [12]. Further utilization of the OHLs could be achieved by increasing the loading of the lines prior to any contingencies by implementing short-time line ratings and other emergency corrective network actions during post fault operation [15-17].

However, there is very limited work done on the evaluation of the risk involved in such practices that quantifies the conductor ageing resulting from such actions. Determining this conductor ageing against the benefits from increased transmission adequacy is very important to justify the increased risk that is associated with these reinforcement solutions.

This paper presents a novel reliability assessment methodology, to quantify the risk of conductor ageing as a result of inexpensive planning decisions to increase OHL ratings and simple operating decisions to increase emergency

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(post fault) rating durations. Furthermore, it investigates, through a preliminary study, the value of such inexpensive high risk planning decisions in increasing network interconnection flexibility.

The next section details the basic thermal uprating methods followed by the methodology implemented for the studies of this paper in section III. The results are presented in section IV with the main conclusions discussed at the end of the paper.

II. METHODS FOR THERMAL UPRATING OF OHLS

The uprating of power transfer capacity of existing OHLs can be achieved in several different ways which can be categorized in three groups depending on their cost and number of required changes as shown in Fig. 1 [18].

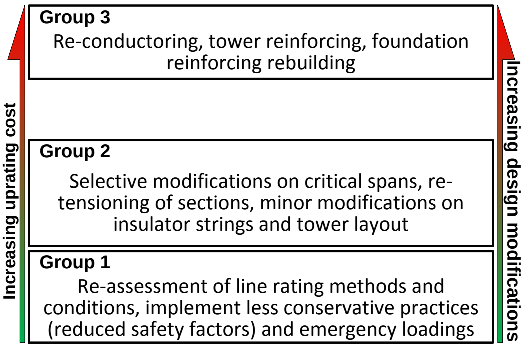

Fig. 1. Grouping of the thermal uprating methods of OHLs.

A very popular approach involves the reassessment of line rating assumptions and safety factors (group 1) used in the initial design of the OHL structure [19]. The most common techniques in this group involve the use of higher conductor operating temperature combined with less conservative weather conditions. Consequently, instead of implementing standard SLR with a single conservative weather value, different ambient temperatures are implemented to determine different SeLR values for OHLs [20]. Usually these values are determined by utilization of historic weather data measurements divided into seasons due to their repeatable nature (i.e., winter is colder than summer).

TVLR is another method that is based on reassessment of line rating assumptions and considers the time varying weather conditions surrounding an OHL. Consequently, TVLR changes in time, in a similar manner as the SeLR, due to weather changes. However, in the TVLR method the step-time is usually small and thus the changes are more dynamic, in the range of hours instead of months or seasons, as in SeLR.

The PLR is also developed based on this less conservative ambient weather rating principle [13]. In this case, the line rating is calculated for a recoded set of historical weather conditions and a certain risk is utilised that indicates the probability of exceeding the rating when the OHL is continuously fully loaded. Thus, this exceedance is under the assumption that the line is 100% loaded throughout the complete set of the recorded weather data and it is usually referred to as excursion. The excursion indicates a probability of exceeding the rating of an OHL only when the probability of the failure is considered. Thus, in order to have an exceedance of OHL rating, a failure should coexist with the unfavourable weather conditions that would result in the current rating to exceed the OHL's rating. This exceedance is usually much less than the excursion time. It is also important to note that the excursion time is a design property of an OHL, while the exceedance is an operating property of an OHL within a network [21]. Thus, increasing the rating of the OHL by implementing higher percentages of excursion values does not reflect the same exceedance on the OHLs as these will depend on the failures and the loading occurred at the time of failure to the remaining of the operating network. This PLR method can be further implemented in combination with increased duration of post fault emergency loading, allowing thus, for increased flexibility during the constraint network operation. Therefore, increased overall utilisation of the OHLs results in better network flexibility at emergency conditions. This method of thermal uprating however requires the coordinated decision of both network OHL designer and network operator/planner.

The group 2 methods for increasing OHL power rating, involve minor selective modifications of some "weak" points along the line, which are usually defined as critical spans. Possible modifications include increasing the height of conductor attachment points, or re-tensioning the conductors along the complete length of the OHL (instead of re-tensioning only at the critical spans). This allows for further increase of the conductor maximum operating temperature which, however, reduces the life of the conductor due to the higher temperatures and tensions that the conductor experiences. Its cost makes it one of the least favourite options of this group.

Further increase in existing OHLs' thermal uprating can be achieved with more expensive and disrupting methods (Group 3 in Fig. 1) which usually require major modifications of the OHL. Common applications are the re-conductoring, reinforcing and re-building of the existing structures so as to allow higher current flow and/or higher voltage level operation. Due to high cost of re-building, the preferred method is re-conductoring of OHL which, sometimes also requires reinforcement of the structure.

Many utilities favour the uprating methods described within Group 1 due to their minimal cost of reinforcement and easy implementation. This is also a result of the future uncertainty on generation and demand as well as increased safety factors implemented during the initial design of many OHLs.

III. METHODOLOGY FOR NETWORK ANALYSIS

Every OHL of a power network experiences different loading throughout a single operating year, mainly due to their different number of failures, loading and ambient weather conditions. Thus, every OHL in a network is expected to have different operating history and ageing. Consequently, the degradation (i.e., the ageing cost) during temporary increased-utilization cycles at critical operating network conditions varies for every OHL. This ageing cost however provides the increased flexibility of the network at most critical emergency moments and it also has an important contribution to customers' quality of supply. Thus capturing this ageing cost against the benefits of the "low cost" practices implemented by utilities is very important in order to quantify the worth of high risk but flexible uprating solutions.

A. Methodology Overview

The OHL ageing and degradation risk as a result of thermal uprating is included within an overall network reliability evaluation approach by the implementation of OHL plant modelling as outlined in Fig. 2. Therefore, additional weather and OHL data are required for the plant modelling to capture the operating temperature profile of every OHL component of the network while the common reliability and network operational data are used for the overall network reliability evaluation.

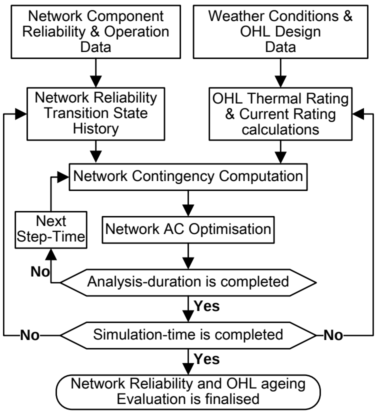

Fig. 2. Calculation flow of network flexibility/reliability and OHL ageing.

Network component reliability and operation data describe the standard mission time oriented parameters, usually a year, thus failure and repair rates of network components (i.e,, f/yr, r/yr) are based on available historical records. In addition, the power network operating limits are specified. These are defined by the generator maximum power output, transformer maximum power rating and impedances, and circuit maximum ratings and impedances etc., as well as the annual load point chronological demand. Furthermore, additional operation parameters are specified related to the emergency loading rating of the lines. Those are the short term emergency (STE) and long term emergency (LTE) loadings of the OHLs as well as their durations which indicate the operator flexibility under constrained network. These data are used to create the network reliability transition state history and assist the network contingency calculations and optimization of power flow calculations.

The weather conditions and OHL design data include historical measurements of wind velocity, incidence angle, ambient temperature and solar radiation. These are location-specific and provided in sequential form. The OHL design related data describe the conductor technology, materials and design, size, resistance, ultimate rating strength and operating temperature. In addition, data that describe the installation of the OHL conductor (installation tension and temperature, design span length) are also included. These data are used to identify the line ratings during the normal and emergency operation as well as to evaluate the amount of thermal ageing developed on the conductor due to operation at temperatures above the designed ones during the contingency events.

Once the network transition state history is defined and OHL ratings are calculated (based on the OHL design properties) then the network contingency computation is performed using sequential Monte Carlo simulation to capture any network failures and their duration. When contingencies are identified at any step-time of the simulation then the emergency (STE and LTE) ratings are utilized in order to increase the network interconnection flexibility. After the emergency rating implementation the ac optimal power flow (ACOPF) is performed and the appropriate indices are recorded. An iterative loop is performed with a step-time that is dependent on the OHL design data (i.e., emergency rating duration) for the analysis-duration (from reliability & operation data) which specifies the time-frame of the analysis and it is usually set to a year. Once the analysis of the system is completed for the initially defined analysis-duration a new analysis is initiated from the beginning which creates a new network transition history. This second loop of iterations stops at a predetermined accuracy criterion defined here as simulation-time, which is controlled by the number of repetitions (determined by the covariance value).

The indices are recorded for every duration and they are updated at the end of the next analysis-duration. The final values are calculated at the end of the simulation.

The calculated indices used to evaluate the network performance implement both the network operating profile as well as the weather conditions. Thus the recorded indices are, the expected duration of load curtailment (EDLC), the expected frequency of load curtailment (EFLC) and the expected energy not served (EENS), the total expected equivalent network ageing (EENA) and expected network annual losses (ENAL).

B. Modelling the rating of network OHLs

The OHL rating modelling implemented is based on two main methods, the SLR and PLR which are time independent and fixed throughout the year and the time-dependent ratings. The SLR is based on the least favorable weather conditions specified in [20], while the PLR with different excursion percentages is also referred to a static line rating values (i.e., SLR-Exc%) [13, 22]. The time dependent line rating models are based on SeLR, which are also implemented in most of the current practices and specified in standards [20], as well as the TVLR.

The line rating calculations, independently of the methodology, are based on the IEEE model [23] with time dependency as shown in equation (1).

$$I(t)=\sqrt{\frac{q_c\left(V_w(t),T_a(t),T_{c,\max}\right)+q_r\left(T_a(t),T_{c,\max}\right)-q_s(t)}{R\left(T_{c,\max}\right)}} \qquad (1)$$

Where q_c, q_r and q_s are the powers for the convection cooling, radiated cooling and solar heat gain mechanisms, respectively. These depend on ambient conditions: incident wind velocity, $V_w(t)$, temperature, $T_a(t)$, and conductor maximum design operating temperature $T_{c,max}$ and resistance at the maximum operating temperature $R(T_{c,max})$. Consequently, the time dependency of the line rating is affected by the weather variables. When weather variables of least favorable conditions (i.e., conservative scenario) are implemented the SLR is calculated, when seasonal weather values are used then SeLR is computed while the PLR is based on the historical data and the design excursion percentage which represents a risk of exceedance. Weather data can be obtained from meteorological stations installed in near proximity to the OHL.

C. Modelling Network OHL States for Felxibility/Reliability

The network reliability under different line rating models for the OHLs and emergency rating operating practices is modelled within the network contingency computation block in Fig. 2. In this block the actions are divided into two groups: the operator decisions and protection automatic design.

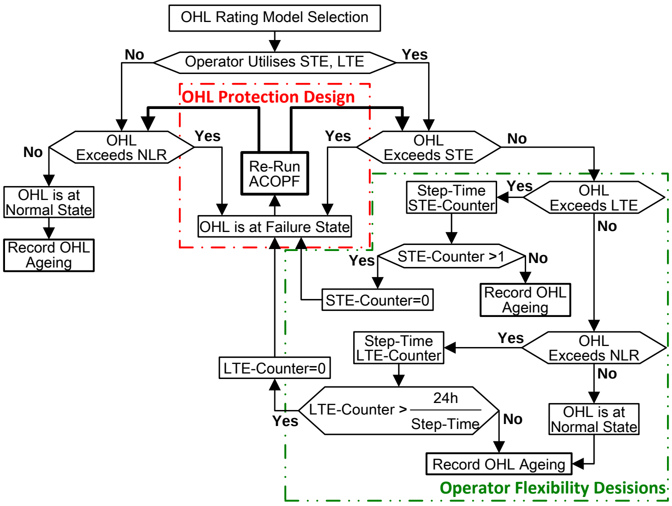

Fig. 3. Network OHL states modelling to capture the OHL ageing.

As can be seen from Fig. 3 when the operator does not utilize the emergency ratings then the OHL protection design determines the operating states of the OHL. However, once the network operator employs the emergency ratings then the OHL protection is set differently. The duration of emergency ratings and the higher rating value, defined here as above STE (ASTE), are utilized within the protection design to fail the line. Consequently, the STE, LTE and their durations are controlled by the operator. The STE-Counter is implemented to determine the duration of the STE (in multiples of step-times) while the LTE-Counter determines the duration of the LTE (also in multiples of step-times).

It should also be mentioned that the flowchart in Fig. 3 is implemented in two dimensions; one to describe the time-domain (defined in step-times) and another to describe the OHL-domain as this loop is performed till the ageing of all OHLs of the network are evaluated for being at any of the designed line ratings.

An ACOPF is re-run again for the same step-time in order to identify any increase in OHL loading as a result of a cascading failure due to OHL protection design activated at any time. This could be the result of exceeding the design period of the operator ratings.

For simplicity of the modeling the maximum duration of the LTE is assumed to be fixed at 24 h in this case. The STE duration is set to be a single step-time.

D. Modelling of OHL Network Ageing

The OHL thermal ageing, $\varepsilon_{OHL,Tc}$, is calculated using (2) for each OHL at any step-time (Fig. 2). Therefore, the conductor temperature, $T_c(t)$, and tension, $\sigma_x(t)$, describe the conductor operating conditions (at any step-time) while the K_x factor describes the conductor type [24]. Then, (3) is utilized to convert the ageing into an equivalent index for every OHL at a single T_c (in this case 100°C) for all conductors during the complete analysis-duration [21].

$$\varepsilon_{OHL,T_C} = f\left(K_x, T_c, \sigma_{OHL,T_C}, t_{OHL,T_C}^{0.16}\right) \tag{2}$$

$$\begin{aligned} \varepsilon_{OHL,100} &= f\left(K_x, T_c, \sigma_{OHL,T_C}, t_{OHL,T_C}^{0.16}\right) \\ &= f\left(K_{OHL}, 100°C, \sigma_{OHL,100}, t_{OHL,100}^{0.16}\right) \end{aligned} \tag{3}$$

Consequently, the complete OHL network ageing (composed of *TOT* number of OHLs) is captured by (4) at 100°C, in hours based on a number of elevated temperature events (ETE) with T_c temperatures and $t_{OHL,Tc}$ durations.

$$EENA = \sum_{OHL=1}^{TOT} \sum_{i=1}^{ETE} t_{OHL,100} = \sum_{i=1}^{ETE} \left(\frac{\varepsilon_{OHL,T_C}}{\varepsilon_{OHL,100}} \times t_{OHL,T_C}^{0.16} \right)^{6.25} \tag{4}$$

IV. CASE STUDY DESIGN

The proposed methodology is implemented on the 24-bus IEEE RTS system [25] with increased loading to 1.5 pu and using additional OHLs design properties to complement the network's line properties provided. Table I illustrates the data used for the OHLs assuming a single conductor installation calculated using [24].

TABLE I. CONDUCTOR PROPERTIES DATA MODELLED

Name	**R_{25C} (Ω/km)**	**R_{75C} (Ω/km)**	**X (Ω/km)**	**B (S/km)**	**D (mm)**	**I (A, [°C])**
Upas (138kV)	0.09396	0.11057	0.45435	$3.392 \cdot 10^{-6}$	24.7	732 [60°C]
Araucaria (230kV)	0.04266	0.05021	0.43381	$3.890 \cdot 10^{-6}$	37.3	1272 [63°C]

The weather data utilized for the different types of thermal rating are obtained from Whitworth Meteorological Observatory [26]. The probability density of conductor operating temperature assuming SLR and maximum loading throughout the year are illustrated in Fig. 4. From the distribution curves the rating data in Table II are used to determine the different OHL rating models. The SLR identified for the conductor models and weather data resulted in 1 % excursion which is a realistic design value. This indicates a very good fit of the selected conductor to the particular network which further supports the appropriateness selected conductor data.

The network analysis is performed for 5 different OHL ratings that are mainly affected by the OHL design and not the emergency loading flexibility the operators may have, while 4 additional scenarios with different durations of emergency loadings are modelled to capture the operator flexibility impact on network. These 9 scenarios are illustrated in Table III.

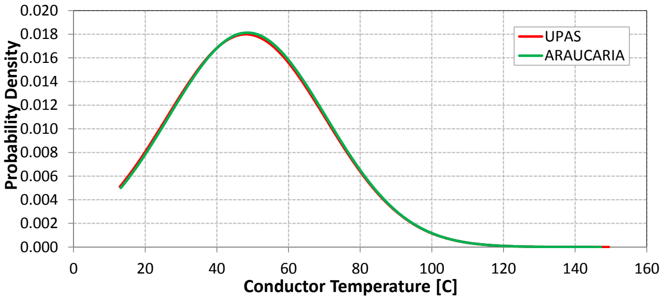

Fig. 4. Conductor temeprature distributions under SLR loading.

TABLE II. AMPACITY VALUES (IN A) FOR THE OHLS RATING MODELS

Rating Model	SLR[b]	SeLR[a]			SLR-0.1%	SLR-12%			TVLR
		20°C	9°C	2°C		Norm	LTE	STE	
Upas	732	732	824	877	317	825	961	1010	Variable
Araucaria	1272	1272	1404	1490	562	1420	1667	1734	Variable

[a] SeLR is implementeding ambient temperatures as defined in [20]

[b] The SLR results in 1% excurtion time (SLR-1%)

TABLE III. NETWORK ANALYSIS SCENARIOS OF OHLS RATING MODELS

Scenario	Sc-1	Sc-2	Sc-3	Sc-4	Sc-5	Sc-a	Sc-b	Sc-c	Sc-b
Rating	SLR	SeLR	Exc-0.1%	Exc-12%	TVLR	Exc-12%			
STD[c]	NA					15m	30m	45m	60m
LTD[d]						24h			
Step-time	1h					15m	30m	45m	60m

[c] STD: Short time emergency rating duration,

[d] LTD: Long time emergency rating duration

V. OVERALL NETWORK ASSESSMENT

The network performance is assessed considering the traditional indices but also additional indices that capture OHL ageing and losses within the network based on the implemented rating modelling practice. Therefore, the resistance of the conductor is calculated at the specific operating temperature for the step-time in order to calculate more accurately the losses.

A. *Impact of thermal rating of OHL Networks on Reliability*

The output data of the analysis for the first 5 scenarios are summarized on Table IV.

TABLE IV. OUTPUT DATA FROM OHL RATING MECHANISM

Rating Scenario	EANL (MWh/y)	EEAI (h/y)	EDLC (h/y)	EFLC (h/y)	EENS (GWh/y)
Sc-1	520	36	140	16	13.96
Sc-2	577	295	137	14	10.35
Sc-3	244	0	596	71	16.07
Sc-4	589	319	169	19	12.81
Sc-5	697	0	60	8	4.99

From Table IV it can be distinguished that the more advance the OHL rating model the better the network adequacy and thus the interconnection flexibility during a network contingency by diverting more power transfer capability through other available lines. However, a closer look shows that the SLE-0.1% excursion is the most conservative OHL rating resulting in zero thermal ageing of the network since the lines do not exceed their designed operating temperature. SLR, which is considered as a method with negligible risk, results in 36h of ageing which is not negligible. When the SeLR is implemented then the ageing is further increased since the loading of the line is also increased. This is due to increased risk that is considered by capturing a season with a single ambient temperature value. The network losses actually reflect the hotter operation of the OHL conductor since the resistance is increased at higher operating temperatures.

In the modelling the SeLR is very similar to the SLR-12% excursion in terms of line ageing. However, SeLR's risk is lower than that of SLR-12% since the latter is based on the common sense of cooler winter and hotter summer conditions that are not considered in SLR-12% rating. This is also evident from the improved EENS response of the network when SeLR is implemented. However, the best performing scenario is the TVLR which has zero ageing and the least EENS indicating its true capacity in providing network flexibility.

B. *Impact of OHL Emergency Rating on Network Reliability*

The outputs in Table V illustrate the impact of network operator flexibility through the emergency ratings. This additional uprating method considers the STE rating varying in time from 15 min up to 60 mins while the LTE is considered fixed at 24 hours.

TABLE V. OUTPUT DATA FROM OPERATOR FLEXIBILITY MECHANISM

Rating Scenario	ENAL (MWh/y)	EENA (h/y)	EDLC (h/y)	EFLC (h/y)	EENS (GWh/y)
Sc-a	687	1703	233	35	18.69
Sc-b	688	1698	193	24	15.73
Sc-c	691	1699	144	20	10.07
Sc-d	692	1698	105	16	6.12

The simulation results in Table V clearly indicate that the extension of the STE duration reduces dramatically the EENS of the network since the operator flexibility is implemented when it is needed most (i.e., during emergencies). Thus the network reliability is improved by providing more time to the operator to respond during contingencies. However, this comes with the expense of increased ageing since EENA has increased more than 5 times from the worse scenario without emergency ratings implementation.

Overall, the most effective rating mechanism is proved to be the TVLR which provides zero ageing and the best EENS performance.

VI. CONCLUSIONS

The paper presents a methodology that incorporates a more holistic perspective for power network analysis. It incorporates advanced modeling of the OHLs that allows capturing the risk of ageing of different flexible thermal rating methods.

From the different flexible uprating methods investigated in this paper the most beneficial is proved to be the TVLR which provides the minimum risk of ageing when compared with simpler practices like SeLR or STR-with-Excursion.

REFERENCES

[1] I. Romero, J. Martin, R. Rivas, L. Wall, and J. C. Sánchez, "Overload Line Controller: New FACTS Series Compensation application based on Switched Series Reactors," presented at the CIGRÉ Session, Paris, 2014.

[2] P. L. Francos, S. S. Verdugo, C. I. Armesto, and D. A. Baeza, "Present and future reinforcements in the Spanish transmission grid allowing to control active and reactive power flows (HVDCs, FACTS and PSTs)," presented at the CIGRÉ Session, Montreal 2012.

[3] P. K. Muttik, R. W. Brown, C. Chalmers, G. Gum Gee, J. Haddow, and N. Pahalawaththa, "FACTS for enabling wind power generation," presented at the CIGRÉ Session, Paris, 2010.

[4] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins, and G. Strbac, "Application of STATCOMs to wind farms," *IEE Proceedings - Generation, Transmission and Distribution,* vol. 145, pp. 511-516, 1998.

[5] M. Masuda, E. Bormio, J. A. Jardini, F. A. T. Silva, S. Copeliovitch, and J. Camargo, "Development and implementation of FACTS (flexible AC transmission systems) devices in distribution networks," in *IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, 2004, pp. 839-844.

[6] V. Salehi, S. Afsharnia, and S. Kahrobaee, "Improvement of Voltage Stability in Wind Farm Connection to distribution Network Using FACTS Devices," in *32nd Annual Conference on IEEE Industrial Electronics (IECON)*, 2006, pp. 4242-4247.

[7] National Grid Electricity Transmission, "Electricity Ten Year Statement 2014", Accessed: March 2015, [Online] Available: http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Electricity-Ten-Year-Statement/

[8] A. Kapetanaki and K. Kopsidas, "Reliability evaluation of demand response and TVTR considering the cost of interruptions," in *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)* 2014, pp. 1-6.

[9] R. Stephen, "Decsription and Evaluation of Options Relating to Uprating of Overhead Transmission Lines," Paris, 2004.

[10] H. Wan, J. D. McCalley, and V. Vittal, "Increasing thermal rating by risk analysis," *Power Systems, IEEE Transactions on,* vol. 14, pp. 815-828, 1999.

[11] D. A. Douglass and A. A. Edris, "Field studies of dynamic thermal rating methods for overhead lines," in *Transmission and Distribution Conference, 1999 IEEE*, 1999, pp. 842-851 vol.2.

[12] F. D. Pullen and D. J. Hopgood, "Probabilistic approaches to transmission line thermal ratings," in *Third International Conference on Probabilistic Methods Applied to Electric Power Systems*, 1991, pp. 191-196.

[13] C. F. Price and R. R. Gibbon, "Statistical Approach to Thermal Rating of Overhead Lines For Power Transmission And Distribution," *IEE Proceedings C: Generation Transmission and Distribution,* vol. 130, pp. 245-256, 1983.

[14] A. Kapetanaki, K. Kopsidas, C. Tumelo-Chakonta, and M. Buhari, "Network planning evaluation implementing time varying thermal ratings," in *International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, 2014, pp. 1-6.

[15] H. Wan, J. D. McCalley, and V. Vittal, "Increasing thermal rating by risk analysis," *IEEE Transactions on Power Systems,* vol. 14, pp. 815-828, 1999.

[16] L. Tan Loc, M. Negnevitsky, and M. Piekutowski, "Expert system application for the loading capability assessment of transmission lines," *IEEE Transactions on Power Systems,* vol. 10, pp. 1805-1812, 1995.

[17] G. A. Davidson, T. E. Donoho, P. R. H. Landrieu, R. T. McElhaney, and J. H. Saeger, "Short-Time Thermal Ratings for Bare Overhead Conductors," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-88, pp. 194-199, 1969.

[18] K. Kopsidas and S. M. Rowland, "Evaluation of potentially effective ways for increasing power capacity of existing overhead lines," in *International Conference on Sustainable Power Generation and Supply - SUPERGEN*, 2009, pp. 1-7.

[19] R. Thrash, A. Murrah, M. Lancaster, and K. Nuckles, *Overhead Conductor Manual*, 2nd ed.: Southwire, 2007.

[20] ENA Engineering Recomendation P27: "Current rating guide for high voltage overhead lines operating in teh UK distribution system," Energy Network Association, 1986.

[21] K. Kopsidas, C. Tumelo-Chakonta, and C. Cruzat, "Power Network Reliability Evaluation Framework Considering OHL Electro-Thermal Design," *IEEE Transactions on Power Systems,* vol. PP, pp. 1-9, 2015.

[22] F. R. McElvain and S. S. Mulnix, "Statistically determined static thermal ratings of overhead high voltage transmission lines in the Rocky Mountain region," *IEEE Transactions on Power Systems,* vol. 15, pp. 899-902, 2000.

[23] "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors," *IEEE Std 738-2012,* pp. 1-72, 2013.

[24] K. Kopsidas, S. M. Rowland, and B. Boumecid, "A Holistic Method for Conductor Ampacity and Sag Computation on an OHL Structure," *IEEE Transactions on Power Delivery,* vol. 27, pp. 1047-1054, 2012.

[25] P. M. Subcommittee, "IEEE Reliability Test System," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-98, pp. 2047-2054, 1979.

[26] Manchester, UK: "The Whitworth Meteorological Observatory ", [Online] Available: http://www.cas.manchester.ac.uk/restools/whitworth/data/index.html