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Review

A Comprehensive Overview of Dynamic Line Rating Combined with Other Flexibility Options from an Operational Point of View

F. Gülşen Erdinç [1], Ozan Erdinç [1], Recep Yumurtacı [1] and João P. S. Catalão [2,*]

[1] Department of Electrical Engineering, Faculty of Electric-Electronics, Davutpasa Campus, Yildiz Technical University, Esenler, Istanbul 34220, Turkey; fgulsenerdinc@gmail.com (F.G.E.); oerdinc@yildiz.edu.tr (O.E.); ryumur@yildiz.edu.tr (R.Y.)
[2] INESC TEC, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal
* Correspondence: catalao@fe.up.pt

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Abstract: The need for flexibility in power system operation gradually increases regarding more renewable energy integration, load growth, etc., and the system operators already invest in this manner to enhance the power system operation. Besides, the power system has thermally sensitive assets such as lines, transformers, etc. that are normally operated under highly conservative static ratings. There is a growing trend in this regard to use the actual capacity of such assets dynamically under varying operating conditions leading to a dynamic thermal rating concept which is referred as dynamic line rating (DLR) approach specifically for lines. This study provides a comprehensive overview of existing perspectives on DLR and combination with other flexibility options from an operational point of view. Apart from the existing review studies more focused on implementation category of DLR concept, the concentration on more operational stage from the power system operation point of view leads the difference of this study compared to the mentioned studies. A categorization of the DLR implementation for either being sole or combined usage as a flexibility option is further realized. Besides, a geographically categorized analysis on existing practical evidence on DLR concept and implementations is also presented in this study.

Keywords: dynamic line rating; flexibility; operational perspective; overhead lines

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1. Introduction

1.1. Motivation and Background

There are numerous thermally limited assets in the electric power system from different points of view, where among them the main assets under more careful consideration can be listed as the transformers and lines (both overhead and underground lines serving for transmission and distribution systems). The thermal limits of transformers and underground lines (ULs) are more related to possible accelerated aging and even physical damage of such assets while overhead lines (OHLs) face also with additional concerns regarding the sag or clearance requirements apart from aging and damage issues that further limit the asset capacity thermally. Therefore, the OHLs are given more specific consideration duly in the literature and industry both from points of view of Distribution System Operators (DSOs) dealing with a more homogenous mixture of ULs and OHLs and Transmission System Operators (TSOs) dealing with a more dominant infrastructure of OHLs over ULs.

The mentioned thermally limited assets are operated under very conservative operational limits to avoid the risk of any malfunction or damage. The mentioned limits are generally static without the consideration of actual operating conditions. The mentioned static ratings for OHLs and ULs are named as well-known Static Line Rating (SLR) which is defined as the maximum allowable current or power to pass through a conductor in order to satisfy a maximum conductor temperature under highly conservative weather conditions. Typical weather conditions considered in this manner for SLR calculation can be exemplified as low perpendicular wind speed of 0.6 m/s, high ambient temperature of 40 °C and full solar radiation of 1000 W/m^2 which are further expected to occur simultaneously [1]. As seen, the possibility of occurrence for such a conservative weather condition is highly low which may correspond to even a few hours in a year in some specific geographical regions. Therefore, it is a reality that the OHLs exposed directly to ambient conditions are utilized well below their actual limits most of the times in a year, which may compel urging new investments those can in real be postponed for a considerable amount of time. Especially for transmission systems where the highly costly investments are generally considered for much longer periods compared to distribution systems, using the actual capacity of OHLs more effectively can result in vital economic benefits from both investment postponement and operational cost reduction points of view. The use of actual time-varying capacities for thermally constrained assets is generally named as dynamic thermal rating which are specifically named as Dynamic Line Rating (DLR) when lines are considered as the case. The use of DLR as a flexibility option in the power system operation has potential to provide many technical and economic benefits which have been evaluated to use in real-time since more than a half century ago. Therefore, many studies have been realized for implementing DLR as an operational option for power systems where many TSOs and DSOs have also invested in DLR technology to increase their operational flexibility and enhance their asset management strategy supported by numerous technology providers for DLR equipment to ease and improve the field implementation and operation.

1.2. Literature Review

The consideration of the DLR issue can be divided into two main categories: The first category is the implementation step covering the DLR enabling technology development and investment stage (monitoring equipment, etc.), and DLR estimation and decision making approach stage with the input gathered from monitored values via the mentioned equipments. The second step is the operation step including the use of DLR decision within power system operation as a source of operational flexibility.

There are several review studies that examine the DLR concept from different points of view. The study of Coletta et al. [2] investigated the different phasor measurement units (PMUs) based temperature estimation driven DLR methods from a theoretical background with relevant method categorizations. Afterwards, the accuracy of the mentioned different PMUs based DLR categories was assessed in a real experimental test bed on a thermally constrained 400 kV OHL in the north of Italy where the impact of uncertainties regarding the operational environment was given further importance with detailed analyses in [2]. Another review on the use of PMUs for DLR implementation together with a discussion on the relevant implementation approaches was also provided in [3].

The study in [1] initiated with a comprehensive overview of existing DLR methods categorized via the monitored magnitudes (meteorological parameters, conductor temperature, sag, clearance, tension, or a combination of these magnitudes) as well as a very detailed information on the industrial practical evidence for technologies used in monitoring the mentioned magnitudes. Besides, there is also a specific section in [1] devoted to the relationship between DLR and wind power integration supported by a practical evidence area dedicated to this specific topic. A brief version of the study in [1] was also presented as an overview analysis on the same topic in another venue by the same group of authors in [4]. A field data based detailed overview of the considerations regarding the selection of proper DLR technique was presented in [5] with very detailed technical details on the different industrial technologies gathered from real implementations.

The study in [6] firstly discussed the benefits of DLR integration from correlated technical and economic points of view followed by a DLR implementation methods oriented detailed analysis with relevant comparisons between the mentioned approaches. A detailed analysis of practical evidence categorized by the applied type of monitoring systems was further propounded in [6] ending with the evaluation of the expected future of DLR systems.

A highly detailed review mainly focusing on the applied forecasting techniques for DLR was provided in [7], starting with a section devoted to a historical background and practical evidence- based information. The impacts of each meteorological variable were analysed in detail followed by sections evaluating the theoretical background and effectiveness of different forecasting techniques as well as economic aspects and limitations of DLR implementation in [7]. The study in [8] also considered the forecasting point for DLR implementation evaluating different approaches in this manner in a detailed way. The field applications of DLR by different system operators were also evaluated in [8] to provide knowledge on practical evidence.

The commercially available DLR oriented technologies together with overview of application methods as well as benefit analyses were also discussed further in other review studies such as [9–12] from different points of view. A very detailed review report on DLR from benefits, challenges, practical evidence and power system stakeholders' insights points of view was further provided in [13] recently by U.S. Department of Energy.

Different from the above referred studies, the review-based analysis in [14] is the sole study considering the DLR topic also from operational point of view. The analysis in [14] initiated with an overview of DLR basics with comparative evaluation of relevant standards as well as an industrial perspective on DLR oriented monitoring devices. However, more emphasis in [14] was given on reliability oriented operational studies in the literature as well as a specific analysis on the effects of joint implementation of DLR and other smart grid technologies on power system reliability. Even the study in [14] was the unique attempt for analysing the operational perspective of only DLR as well as combined approaches including DLR, the analysis was limited to reliability topic without considering the other areas preventing a broader perspective on the existing proposed methods.

The aforementioned studies have contributed well to the wider evaluation of DLR to implement in power system operation. However, majority of these review studies were mainly focused on the implementation stage rather than the studies and approaches in the operational stage, which is a vital issue for wider acceptance of DLR concept as the main stage to observe the relevant benefits.

1.3. Contributions and Organization of the Paper

In this study, a comprehensive overview of existing perspectives on DLR and combination with other flexibility options from an operational point of view is realized. Summarized background information as well as a geographically categorized analysis on existing practical evidence on DLR concept and implementations is presented initially. Afterwards, a detailed operational categorization of existing studies on DLR based on a sole use of DLR or a combined flexibility based operation including DLR is provided by a dedicated approach. Therefore, the contributions of this review study compared to other DLR overview analysis-oriented studies can be summarized as twofold:

- A comprehensive analysis from the operational perspective of DLR techniques in the power system is provided as an area that has not been well-covered in the existing review studies compared to the detailed consideration in this study.
- A distinction in terms of the used flexibility options is also provided in this study for the first time in the relevant review-oriented literature. Accordingly, apart from a deep analysis on the operational problems considering DLR as the sole flexibility option, a further detailed evaluation on the combined use of DLR with other operational flexibility options is also conducted, which is an increasing trend in the recent studies as also visualized in the trend analysis of the DLR implemented operational studies realized within this study.

The remainder of the study is organized as follows: Section 2 presents summarization of existing background information on DLR including a further practical evidence analysis. Then, Section 3 provides the aforementioned comprehensive analysis of the relevant DLR operational stage-oriented literature. Finally, the concluding remarks are given in Section 4.

2. Overview of DLR Background Information and Practical Evidence

2.1. Summarized DLR Background Information

The analysis of thermal dynamics related rating of lines mainly goes back to the investigation of House and Tuttle [15] after the previous investigations even before World War II [7]. The thermal dynamics-based limits are more related to shorter lines (shorter than 100 km) when longer lines are restricted dominantly by voltage and stability limits. The OHLs have also further limitations such as sag and clearance safety limits compared to ULs regarding the thermal concerns. Therefore, the thermal limits are the one of the major drivers for the effective utilization of the existing line capacities.

Specifically for OHLs, the time varying nature of ambient conditions has vital impacts on the actual ampacity of the conductor. Therefore, exploiting from the actual ampacity level of a conductor by DLR implementation firstly relies heavily on effective monitoring the relevant magnitudes on the site. The monitored magnitudes to estimate the time-varying conductor temperature in order to further decide the DLR of the line reveal the basis of the categorization regarding the implementation of DLR [1]. Herein the main issues are the observation of the ambient, thermal, mechanical states of or around the conductor detailed as follows:

- The ambient states-based approaches: The ambient states around the conductor are mainly determined by monitoring the weather magnitudes composed of wind speed, wind direction (sometimes neglected by considering directly the perpendicular wind speed to the conductor), solar radiation, ambient temperature, precipitation (rarely used). Using the ambient states around the conductor as well as the line loading, the calculation of the conductor temperature through mathematical models defining the conductor thermal behaviour is mainly realized by the well-known standards by CIGRE [16] and IEEE [17] (initiated in 1986 with updates in 1993, 2006 and 2012 where a new update is also under preparation). The ambient states based techniques are easy to implement with low costs, but lead a more risky condition as the ambient conditions (especially wind speed) may vary vitally along the line span due to terrain conditions as well as impact of geographical position and the estimations may mislead the operator during actual operation regarding the actual line potential without causing adverse conditions.
- The thermal states-based approaches: The thermal states based approaches mainly rely on real-time conductor temperature monitoring to estimate the line loadibility. In the mentioned approaches, one of the main concerns is that the surface temperature monitoring gives a local temperature value and this can change in different parts of the line that are not monitored regarding ambient conditions.
- The mechanical states-based approaches: The mechanical states based approaches are mainly based on sag, clearance or tension monitoring for the line as depicted in Figure 1. In these methods, the conductor temperature is estimated through mechanical models defining the relationship between the conductor temperature and sag, clearance or tension values where the increase in conductor temperature has a directly proportional relationship with the sag and an inversely proportional relationship with the clearance and tension. There is also a direct relation between tension and sag/clearance depending also on the span length and unit length weight of the conductor. A further vibration monitoring technique that can be considered in this class of approaches is also available even this technique is not widely used. The most important advantage of the mechanical states based approaches is that they give an estimation of the thermal status along the whole span rather than a local data gathered from direct temperature monitoring oriented thermal states based approaches.

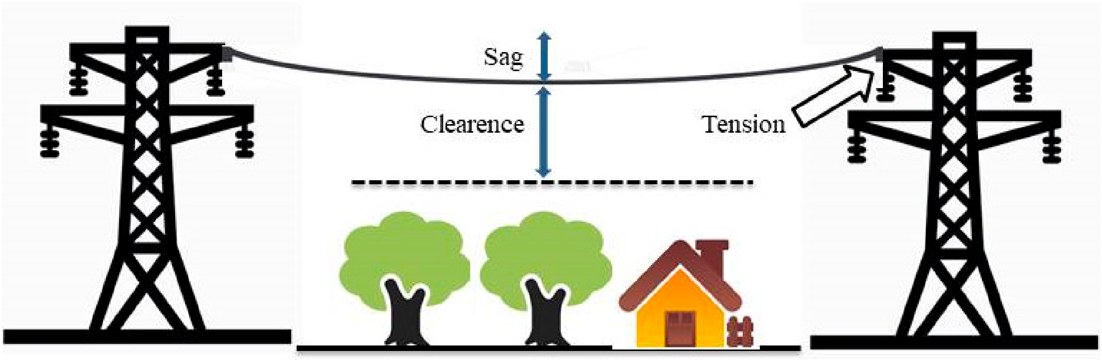


Figure 1. Depiction of mechanical states based approaches.

Apart from the aforementioned methods, there are also different approaches which can further be categorized as other methods such as conductor replica, electromagnetic field monitoring, etc. to gather line sag or loading, conductor temperature, etc. data. In order to verify any forecasts with real field observations, generally the above mentioned approaches are used in a combined way in the field (e.g., the ambient states based estimation oriented approaches are supported in general by thermal or mechanical states monitoring systems to secure operational safety). Several technologies also exist and already maturely applied in real examples for monitoring the aforementioned magnitudes to enable handling the field data used by a decision making system to decide the actual DLR for a conductor during any time period. These technologies are comprehensively detailed in several studies such as [1,5,6] which readers are referred for further discussion.

There are several benefits of implementing DLR within power system operation. The leading benefits which can be enabled by DLR are summarized as follows:

- Congestion reduction and accordingly reduced congestion costs due to less need for generator re-dispatching (especially for employing more costly generators), load shedding, and renewable energy systems (RESs) based generated power (especially wind power) curtailment (major system operators in U.S. faced with a total of 4.8 billion $ congestion costs in 2016 [13], which can be considered as a vital value that may better enlighten the importance of reducing congestion in power systems)
- More wind power integration as there is a well-known correlation between wind power and DLR increase as higher wind speeds increase wind power production as well as DLR due to increased cooling by wind
- Additional economic benefits apart from congestion cost reduction such as deferred line investments in return of a considerably lower cost for the investment of the required infrastructure for DLR (the availability of DLR is considered to also have the potential for further decreasing the electricity prices in the market due to enabling to host more amount of economic RES power)
- Reliability and resiliency improvement by improving the system operator's awareness on the real time status of the line as the critical dynamics are already monitored by the DLR enabling equipment
- Enhancing power system flexibility enabling also a step in transition to the operation of the power system in a smarter manner

Naturally, there are also challenges and issues to further consider for a wider acceptance of DLR concept which can be listed as follows ([6,7,13]):

- Selecting the suitable lines (providing more benefits due to being highly congested, enabling DLR implementation due to being physically proper, etc.) to apply DLR
- Confidence of the conservative system operators on the estimated ratings, or unwillingness of the system operators regarding the additional complexity on power system operation in other means

- Uncertainty regarding the actual beneficiary of DLR based economic gains (even it is widely accepted that DLR will bring many economic benefits, the problem is to actually define who will benefit from this)
- The need to statically or even dynamically adapt other operational issues such as protection settings, etc. to the new conditions provided by DLR
- Concerns on measurement and modelling accuracy and reliability
- Lack of sufficient knowledge and experience hindering the increased willingness of the aforementioned conservative system operators to apply DLR solutions

It is a vital issue to put sufficient efforts to cope with the aforementioned challenges for a wider actual implementation. Therefore, specific emphasis on a discussion regarding these challenges is given herein. First of all, among the possibly huge number of lines of a specific power system portion, many of them have very high congestion problems to make DLR investments suitable. There are very specific lines especially in high correlation to wind power plant investments (that is a widely evaluated issue in the literature as will be discussed in Section 3) causing even renewable power curtailments that unfortunately affects the economy of the power system operation in a very adverse way. Therefore, it should be techno-economically analysed for each partition of the power system regarding the fact that either in investing a new line or such DLR solutions would be more beneficial. On the other hand, to persuade the system operators for investing in such considerably new technologies in their system mostly having been operated without much change in the strategy for long periods, the DLR solution should be supported with proven results in terms of sufficient improvements in system performance and economy. When the number of applications in different regions with different operational and economic conditions increase, it will be easier to see the ways to handle any insufficient experience and relevant reluctance for implementing DLR solutions.

Considering the benefits as well as challenges to tackle with, the DLR has already been considered as an applicable flexibility option within power system operation to transform the existing power systems to a Smart Grid [7]. Therefore, many system operators already have installed DLR technologies which will be summarized in the practical evidence oriented upcoming subsection.

2.2. *Practical Evidence*

The practical applications of DLR by system operators spread into different regions of the world from Far East Asia to Europe and America. For Europe, the application by Red Electrica de España (REE) and Iberdrola in Spain on a 400 kV transmission line in 1998 can be given as a pioneering example [18]. A mechanical states based approach was employed in Belgium by Elia as a TSO in 2008 during a collaborative research project with University of Liege [19,20], with a further initial implementation of a similar system in 2010 by RTE in France [19,21] on 150 kV, 245 kV and 400 kV transmission lines. The transmission system of Italy operated by Terna Rete was equipped with DLR systems by the roll-out studies till the end of 2015 [22] based on a synchrophasor measurement system. An application on a 110 kV double-circuit transmission line between Omagh and Dungannon was applied by Northern Ireland Electricity in 2009 [23]. Other trials in the North Europe was conducted in UK by E.ON Central Networks as a current subpart of Western Power Distribution Company for wind power integration enhancement in the English East Midlands. Scottish Power (SP) Energy Networks as a DSO as well as a TSO in Central and Southern Scotland, North Wales, Merseyside, Cheshire and North Shropshire within UK implemented a DLR system on a 33 kV network between Cupar and St Andrews in North Wales as well as in a part of 132 kV transmission system [24]. A 30 km 132 kV transmission line-based implementation of a mechanical state based approach was conducted by Scottish&Southern Electricity Networks [25]. There are also further reports on the application of DLR solutions in Europe within different countries such as Austria [26] and Finland [27], where the analysis in [26] gives a further comparative analysis regarding field data regarding the application of DLR on either mountainous or flat landscapes.

As far as America is concerned, north part of the continent is dominated by U.S. and Canada regarding DLR applications in this region of the world. In U.S., Idaho DLR project with the collaboration of Idaho Power and Idaho National Laboratory initiated an application of DLR solutions on a total 450 miles of transmission line between 2013 and 2018 [28]. Pennsylvania- Jersey-Maryland (PJM) Interconnections and American Electric Power (AEP) collaborated for implementing DLR solutions on the Cook-Olive 345 kV transmission line between Michigan and Indiana managed by AEP, where over 4 million $ of reduction in congestion costs was obtained in the first year of field application [29]. New York Power Authority (NYPA) applied multiple DLR projects especially near large hydroelectric plants on 345 kV Niagara-Rochester, 345 kV Gilboa-Fraser and 230 kV Modes-Willis-Plattsburgh transmission lines [30]. Oncor installed DLR technology on eight different transmission lines between 138 kV and 345 kV voltage levels enabling an increase of line ampacities up to 14% [31]. Kansas City Power and Light (KCPL) investigated DLR to overcome congestion on 345 kV 32 miles LaCygne-Stilwell flowgate avoiding significant costs regarding generator re-dispatching [32]. Regarding the examples in Canada, AltaLink invested on DLR concept in 2015 in order to enhance wind power integration resulting in an increase of 22% in this manner [33]. Hydro Quebec also implemented DLR solutions based on SMARTLINE technology on a 735 kV transmission line in Quebec [34] while a former long-term application was realized by Hydro One (formerly known as Ontario Hydro) in Ontario [35]. One of the unique examples from south part of the continent was from Brazil employed to a Brazilian river crossing project [36]. Many more applications are also under planning stage as the American continent lags behind in DLR investments compared to Europe as stated in [13].

For the cases of DLR applications in Asia and Australia, the application of Korea Electric Power Corporation (KEPCO) can be considered as one of the pioneering DLR applications in Asia enabling an increase of line ampacity up to 35% [37]. An initiative by World Bank to Smart Grid solutions- based enhancement of power transmission in Vietnam included a separate DLR application to cope with the concerns regarding rapid load growth-based line ampacity insufficiencies [38]. The Transpower Company in New Zealand started to explore the possible benefits of DLR within the relevant transmission system operation in 1996 with trials on field initiated in 2012 [39]. TransGrid in Australia also provided applications on the ambient states based DLR in the concept of asset efficiency improvements [40]. There are also many applications under investment planning or under investigation stages in different regions of the world representing the growing importance of DLR in more effective electric power system operation. A general overview including some implementation notes and field results regarding some of the aforementioned applications of DLR in different regions of the world is depicted in Table 1.

Table 1. Overview of practical evidence regarding applications of DLR in different regions of the world.

Continent	Country	Some Implementation Notes and Field Results
Europe	Spain	• Implementation Year: 1998 • Implemented by Red Electrica de España (REE) and Iberdrola on a 400 kV transmission line in the ring of Madrid • Based on previous attempts during a project called "Implantation of Dynamic Thermal Rating in Real Time in the Overhead Transmission Lines (DITER)" supported by Spanish Electrotechnical Research Program (PIE) and initiated in 1993 • Four weather stations were installed in four substations located in Galapagar, SS Reyes, Loeches and El Hornillo covering the different corners of Madrid zone to enable an ambient states based approach. The implementation of monitoring equipments was finalized in 1997. • The time granularity for DLR recalculation was 15 min.

Table 1. *Cont.*

Continent	Country	Some Implementation Notes and Field Results
		• The results were analysed for different lines in terms of steady state loading and short-term loading (up to 20 min) capability of the lines. The short term loading capability could reach even 40% more of the steady state loading value for some lines. Even for the worst case, the short term loading was at least 5% more than the steady state loading capability.
	Belgium	• Implementation Year: 2008 • Realized by Elia as the Belgian TSO in collaboration with University of Liege under the project called "Ampacity Monitoring (Ampacimon)" • A mechanical states based approach currently applied in 27 different transmission lines in Belgium • Regardless of the DLR calculation, the allowable upper limits are restricted as 105% and 109% of the line capacity during peak and off-peak hours.
	France	• Implementation Year: 2010 • A follow-up mechanical states-based approach for the Ampacimon implementation of Elia in Belgium • In Bretagne implementation site, it was found that it is possible to use the OHLs with 1200 A SLR over 1400 A more than 50% of the time even reaching 1.5 and 2 times of the SLR capacity for some periods of the year accordingly for summer and winter.
	Italy	• The roll-out implementation Year: 2015 • Implemented by Terna Rete as the Italian TSO responsible for 63,500 km of high-voltage power lines • A mechanical states-based approach including temperature sensors and synchrophasor measurement units partly or fully implemented on different OHLs with 150 kV, 220 kV and 400 kV voltage levels • Reduction in wind power spillage was obtained by selecting specific OHLs close to wind power plants (from nearly 8% to 1% for some years between 2011 and 2017)
	UK&Northern Ireland	• Multiple applications in Northern Ireland, English East Midlands and North Wales by different companies including Northern Ireland Electricity, E.ON Central Networks (a subgroup of Northern Power Distribution Company), SP Energy Networks, Scottish & Southern Electricity Networks, etc. after 2009 for short lines with different voltage levels from 33 kV to 132 kV. • The results of Project FALCON revealed on September 2015 by Northern Power Distribution Company presented 80% transient and 50% mean increase in line rating compared to SLR for some 11 kV OHLs even a safe temperature margin below the maximum allowable temperature was left.
America	US&Canada	• Multiple applications in Idaho, Michigan, Indiana, New York, Kansas City etc. in US by several companies including Idaho Power, PJM Interconnections, AEP, NYPL, KCPL, Oncor, etc. mostly for 345 kV and partly for lower voltage (138 kV, 230 kV) OHLs • The application in Idaho resulted in over 15% and 10% increase in OHL rating respectively for short term (15 min–60 min) and short term look ahead (60 min–4 h) time periods. • The application by PJM and AEP resulted in 4 million $ of reduction in congestion costs. • NYPA used a total budget of $1.44 million (in collaboration with Electric Power Research Institute) for DLR application partly supported by Smart Grid Demonstration Program of US Department of Energy. The results revealed more than double capacity use possibility for some OHLs during 15 min based short term DLR. • The application of Oncor enabled an increase of line ampacities up to 14%. • The implementation of AltaLink in Canada resulted in an increase of 22% in line ampacity.

3. Comprehensive Overview of DLR Integrated Operational Perspectives

As aforementioned before, the DLR concept in power systems can be categorized into the implementation and operational categories. Herein, the operational category where the DLR is already a flexibility option in the electric power system operation is evaluated in this section with a comprehensive overview of the existing literature on the exact topic. The relevant literature is further divided into two parts named as solely DLR based operational flexibility oriented studies and combined flexibility oriented concepts including DLR as one of the options. From the expression of "solely", it should here be clearly noted that the very mature resource of flexibility from conventional generators based power production is not considered as an "innovative and considerably new type" of flexibility in power system operation and therefore in all the below given explanations considering the DLR based flexibility either from "sole" or combined" points of view already include the mentioned conventional generators based constrained power up or down regulation based flexibility. Besides, majority of the studies also consider the load shedding based demand manipulation option even as a last resort flexibility, but this option is not also considered under the concept of demand side solutions in an updated and innovative manner and disregarded as a smarter operation based flexibility option in this study.

3.1. Solely DLR Based Operational Flexibility

There are operational concepts oriented studies specifically focused on the integration of RES units into the electric power system constituting the majority of the literature for solely DLR based operational flexibility. Among them, Wallnerström et al. [41] firstly proposed a new model for DLR calculation as a function of SLR, wind speed and temperature as a simplified version of widely used and aforementioned IEEE and CIGRE standards. The Authors in [41] further realized detailed comparisons of the results of the proposed model and far more detailed relevant IEEE standard based model to depict the simplified model validity. The maximum underestimation and overestimation of the simplified model were found respectively as 3.27% and 1.13% in [41]. Then, the study in [41] exemplified a comparison of the proposed DLR approach based on both wind speed and temperature with other possible operational approaches (different SLR levels and DLR levels varying based on either wind speed or temperature) from life cycle cost analysis and curtailed wind power points of view by the implementation of an economic optimization simulation model. A recent study on wind power integration correlation with the DLR potential was investigated in [42] using the two-bus test system representing the wind power connection bus and the main grid bus for solely concentrating on the impacts of limitations of the transmission OHL only dedicated to the wind power plant on wind power curtailment. In this manner, the mentioned study in [42] therefore neglects the effects of any load or different generator dynamics on a further congestion on lines and found out an increment of more than 20% wind power acceptability along some of the evaluated wind farm types based case studies for China.

Banerjee et al. [43] conducted a congestion prevention strategy during outage conditions of both N-1 and N-2 by DLR implementation in order to reduce wind power curtailment or re-dispatch. The operational cost minimization-oriented study in [43] defined a cost variable for DLR implementation as a constraint relaxation penalty apart from the other cost components regarding conventional generators based power production, wind power uncertainty and congestion. The mentioned study in [43] also considered the stochasticity of wind power production in the evaluation as a notable difference compared to many existing DLR based operational studies. An interesting study considering also the stochasticity of wind power as well as the load demand, component availability and weather variables (wind speed, solar radiation, ambient temperature) leading to a stochastic DLR capacity as the overall resources of uncertainty in the system operation was portrayed in [44]. It should here be noted that the conventional generators and transmission lines were the assets considered regarding the stochasticity of component availability from outage point of view in [44]. Therefore, the mentioned study in [44] declared a two-stage stochastic programming based cost minimization oriented security constrained unit commitment problem and obtained a cost saving of more than 7% and a reduction in wind spillage around 1% during different tests using the synthetic data of 6-bus and IEEE 118-bus systems.

A day ahead dispatch strategy including chance constraints representing DLR uncertainty and a DC equivalent optimal power flow employed to a wind power dominated power system was proposed in [45]. The mentioned operational cost minimization-oriented study in [45] considered the non-parametric probabilistic approach based on Gaussian Mixture Model for DLR and wind power uncertainty. The tests in [45] resulted in a reduction of more than 55% in wind curtailment levels as well as more than 17% in total operational costs for different case studies conducted in a modified version of IEEE RTS 24-bus test system. The study in [45] also considered the comparison of the results from a deterministic to non-parametric distributions-based consideration of the DLR and wind power uncertainties. From a different point of view, the study in [46] specifically focused on the impact of DLR implementation on wear and tear, and accordingly the mechanical stress and reliability of aluminium conductor steel reinforced (ACSR) cables based OHLs. The mentioned study in [46] dealt with a conventional generators-based power production cost minimization oriented DC optimal power flow problem for a system including wind power and compared different DLR schemes. The mentioned different schemes in [46] were based on time granularity or frequency of line capacity change (1-h, 2-h, 3-h and 4-h time steps) from the point of view of varying line capacity limit cycles' impacts on ACSR conductors' durability as well as wind curtailment and operational cost. The case study in [46] conducted on IEEE RTS 24-bus test system modified by a portion of Swedish Power Market data resulted in a slightly over 1% reduction of operational costs and nearly 6.5% of wind power curtailment for all DLR implementation frequencies. Herein, longer steps of DLR chance resulted in a reduced wear and tear level on ACSR conductor, as a vital result for real implementations of DLR indicating the importance of maintaining DLR frequency at minimum if possible as depicted in [46].

A real case within the service area of Viesgo as a DSO was presented in [47] using three years of data from 2015 to 2018. The DLR system in [47] was designed to include both weather stations, power quality analysers and conductor temperature sensors as the system hardware. The mentioned system in [47] considered an additional safety coefficient of 80% for the operational maximum conductor temperature to avoid any risks regarding the DLR decisions. The DLR system in [47] enabled the supply of 70.9 GWh of more wind energy leading to 7800 tons of CO2 savings. The initial results of the mentioned real application belonging to year 2015 in [47] together with a deeper theoretical background were also presented by a similar group of authors in [48]. The study conducted by Simms and Meegahapola in [49] initially made a detailed sensitivity-based comparison between IEEE and CIGRE standards. The Authors of [49] further realized an analysis on the impact of the selection of the standard to follow on the system operation in wind power rich power systems. The case studies conducted on The New England 39 bus test system using DigSILENT Power Factory software were initiated by selecting the proper candidate lines to apply DLR. The analyses then preceded with a comparative analysis especially focusing on the power loss reduction of DLR implementation reaching to slightly over 3.5% in [49].

There is also a group of studies conducted by a Banerjee et al. in [50–56] aiming to enhance the wind power integration and improve power system operation during wind power integration for transmission level either from a deterministic, probabilistic or stochastic point of view. In [50], the objective of the stochastic optimization problem was to minimize a combined cost function composed of conventional generation costs, wind and reserve costs, DLR-based temporary line capacity relaxation cost and congestion cost components. The same objective function was also applied in [51] resulting in 54% enhanced use of line capacities during a case study on IEEE 14-bus test system, and further evaluations considering the risk of uncertainty in DLR decisions and system response during N-1 and N-2 conditions were also conducted respectively in [52,53]. The cost of DLR based varying line capacity was also a part of the objective function defined in [54] evaluating the impact of DLR on wind power curtailment by a case study conducted using IEEE 14-bus test system.

On the other hand, the probabilistic approach implemented in [55] considered the minimization of conventional generation and wind power feed-in tariff based dual components based total costs resulting in 60% reduction in reserve requirements and 49% reduction in operational costs with DLR implementation during tests conducted using a sample 3-bus test system. A similar probabilistic approach was implemented also in [56] enabling a reduction in 12% in line overload and preventing wind curtailment with the DLR implementation.

There are also many more wind power enhancement or wind power integrated systems' advanced operation-oriented studies for DLR supported transmission systems [57–71]. A DLR application in Mexican National Electric Grid considering all different subgrids of 115 kV, 230 kV, and 400 kV was considered in [57]. The mentioned study in [57] especially demonstrated the direct correlation between DLR based congestion cost alleviation potential for the OHLs close to wind power plants. The field data for applying DLR for the lines connecting wind power plants and hydroelectric plants were shared in [58,59] by Terna S.p.A as the Italian TSO. A two-stage stochastic co-optimization model for energy and reserve allocation considering DLR forecast errors in the second stage of the process was proposed in [60] and tested using a wind power integrated IEEE 24-bus sample system. The model in [60] was enhanced in [61] also by considering the stochasticity regarding wind power generation and line outages apart from the DLR decisions. A probabilistic analysis considering the risks associated with the wind power curtailment as well as line overloading to evaluate the benefits of DLR implementation was presented in [62] and tested using modified IEEE 14-bus network model. A case study for analysing the wind power integration improvement by DLR implementation for Northern Germany was evaluated in [63] and the same issue was also considered in [64] with a further optimization model for the transmission network operation in the Humber Estuary region, UK. A study on active power loss minimization by optimal allocation of wind power plants based reactive power supply units considering DLR based varying network constraints was assessed in [65] using IEEE 30-bus test system structure and Northern Ireland Power System demand and wind data. In [66], DLR was proposed among a set of alternatives to effectively cope with N-1 conditions during electric power system operation for a real 15-bus 130 kV network in Sweden and was found to be one of the most powerful methods. A probabilistic weather-based optimal power flow model for maximizing wind power integration was tested in [67] considering the uncertainty in wind power production. The correlation between wind power generation and DLR was specifically analysed in [68,69]. The reliability impact of DLR on a wind power dominated power system was discussed in [70], and a similar problem combined with stochastic optimal power flow was taken into account by [71].

There are comparatively very small but increasing number of studies focusing on photovoltaic (PV) based solar power correlation with DLR compared to wind power oriented competitive literature. Among them, a very recent study conducted by Li et al. [72] provided an accommodated PV power maximization oriented optimization model for a combined operational constraints integrated planning problem for a distribution system instead of many studies considering a transmission system condition leading to treat the PV system more as a distributed generation unit. A modified forward/backward sweep power flow model-based implementation of network constraints with a temperature dependent resistance model was applied in [72] on a sample 14-bus test system. The tests in [72] resulted in an increase of slightly over 5% accommodation with DLR availability under proper weather conditions as well as under more beneficial selection of the integrated bus in the network model by sensitivity analyses. Besides, the possible adverse effects of high radiation and high ambient temperature conditions that may even lead the DLR to be below SLR with a high possibility to coincide with high PV power production in specific periods of the year was also given specific importance in [72]. This may pose more realistic real operational constraint that the system operator may have to tackle for such an implementation. A combined geographical information system and weather parameters based DLR concept was proposed in [73] for application in operational cost (composed of fuel, start-up and shut-down costs of generators) minimization oriented security constrained unit commitment problem solved by a binary real coded particle swarm optimization method. The presence of PV based generation unit was also considered as an additional case where the uncertainty in PV production was deterministically considered using a white Gaussian noise over the forecasted PV production. The results obtained using IEEE 30-bus test system in [73] enabled a reduction of nearly 3% in operational cost with DLR compared to SLR where the presence of uncertainty in PV production was also proven to add a slight increase in operational cost. Another study in [74] dealt with the implementation of dynamics of DLR in a PV injected power system rather than steady-state characteristics based DLR calculation enabling the consideration of thermal inertia of OHLs. A similar analysis by a similar group of Authors in [74] can also be found in [75]. There are also studies considering both wind power and PV systems in a DLR supported flexible system operation concept [76–78], while the study in [79] considers the DLR supported RES integration without declaring the specific type of RES.

Apart from the RES and DLR combination-oriented studies, there is a group of studies considering the sole DLR implementation from power system protection point of view. The static protection schemes are generally composed of longer term static settings for protection equipment such as relays, etc. However, with the dynamically changing consideration of line capacities via DLR obligates also the protection setting to adapt to these operational changes in order to avoid undesirable tripping actions enabling an adaptive protection scheme. The study of Staszewski and Rebizant in [80] provided a sequential approach for implementing the DLR based varying line current limits into the settings of overcurrent relays. The line temperature and the derivative of the line temperature were both considered in the dynamic DLR enabled protection setting decision making process in [80] was proven to be efficient during a case study for Poland operating conditions in terms of leading the line to be operated even under possible overloading conditions effectively without any operation interruption as well as system failure. The use of DLR for reducing the risk of unnecessary generator tripping cases was proposed in [81] for overcurrent protection schemes by exploiting the advantage of larger thermal time constants of transmission lines compared to electrical time constants. The effectiveness of the proposed approach in [81] was tested using the data of National Grid Smart Zone composed of six 400 kV substations connected to each other by eleven transmission lines revealing effective results even in worst case conditions. A former version of the more advanced study in [81] can also be found in [82]. There are also other studies on DLR supported overcurrent protection in [83–88] and distance protection [89,90] schemes.

There is another specific group of studies analysing DLR supported system from reliability point of view. The OHL design technologies and the relevant ageing risks were integrated as a contributing point to a holistic Monte Carlo based reliability evaluation for DLR supported transmission systems by the study of Kopsidas et al. [91]. A risk and reliability concept integrated operational structure aiming to minimize load curtailment costs was proposed by Teh and Cotton [92] for the reliability assessment of DLR concept including a weather estimation model. There are also further studies by a similar but larger group of Authors of [92] summarized as Teh et al. in [93–95] on topics from the impact of loading to communications on reliability of DLR integrated power systems. The risk aversion based operational cost minimization-oriented study of Dupin et al. [96] and ICT based reliability evaluation-oriented study of Cruzat and Kopsidas [97] can also be given as the other existing reliability based studies for DLR implemented power systems.

A group of sole DRL support oriented operational flexibility from a generic point of view (the reason these studies are categorized as “generic” is that the mentioned studies do not consider the problem from a RES, protection, reliability, etc. specific point of view) reveals also an important part in the relevant literature. Among them, as one of the pioneering studies in the field of investigating the performance and outcomes of solely DLR based flexibility on power system operation, Chu [98] analysed the impact of DLR on contingency prevention by realizing a security constrained economic dispatch and then determining the lines with the biggest impact on the overall contingency based cost increment. Moreover, the relevant fuel cost savings by reducing the need for “off-cost generation” were also calculated on the mentioned contingently overloaded lines in [98]. Herein, DLR was applied in [98] to determine the candidate lines with the biggest financial return in such an implementation considering the real operational approach of Philadelphia Electric Company (PECo) as a member of the PJM Interconnection. Another mature study on the impact of adaptive forecasting based DLR implementation on a transmission network operation was carried out in [99] on a 5-bus 230 kV transmission test system. The study in [99] resulted in 18% of more economic benefit compared to SLR even the line losses increased during DLR implementation case. The study of Nick et al. [100] proposed a DLR based security constrained unit commitment problem formulation with linearized AC power flow constraints. The problem was decomposed into master and subproblems (composed of multiple subparts to check network constraints under normal operation and contingency conditions) using Benders decomposition method in [100]. Several case studies in [100] considering generator and line outages on a sample 5-bus network and IEEE 118-bus test system resulted in a reduction of nearly 20% in generator scheduling costs by implementing DLR compared to SLR case. A simplified earlier version of the study in [100] was also given in [101]. A brief case of presenting a congestion management strategy with DLR was proposed in [102] where system-wide evaluation on all available lines instead of selected lines for DLR was conducted from distributionally robust manner. The test case realized using a revised IEEE 73-bus (RTS-96) test system resulted in a reduction for load shedding reaching to 80% in [102]. A real time transmission system congestion management algorithm including the DLR from a quasi-dynamic point of view rather than steady state DLR calculation was proposed in [103]. The results of the simultaneous cost (composed of generation rescheduling and load shedding-based cost components) and congestion clearing time minimization oriented approach in [103] was implemented to modified IEEE 30-bus test system resulting in a decrease of slightly higher than 7% in operational costs.

In [104], a robust optimization approach to tackle with the uncertainty regarding the DLR value of the OHLs was proposed and tested using IEEE 96-bus sample system. Another study dealing with the DLR as well as load demand-based uncertainties via a stochastic approach was presented in [105] for a transmission expansion planning problem. The uncertainty of DLR conditions was also handled in [106] using affine arithmetic approach. A detailed structural analysis for the electrothermal dynamics of OHLs was conducted in [107] as a contribution that was further combined with a load flow analysis on IEEE 14-bus sample power system model. The relaxation of conventional load shedding strategies with DLR was considered as a different point of view in [108] through a power system security and loss load consideration confidence-oriented optimization problem. Inserting DLR into contingency analysis was proposed in [109], while the control of conventional generators based distributed generation units through the relevant DLR values was the main contribution of [110]. A specific emphasis was given to the sensitivity of DLR decisions on environmental inputs in [111] while combining the DLR with energy dispatch problem. Similarly, the security constrained economic dispatch and optimal power flow combined with DLR were also considered in [112–114]. The impact of DLR implementation on improving the available transfer capacity was specifically discussed in [115,116]. A linear programming-based optimization implemented for two different minimization oriented objectives of either power losses or generation costs was proposed in [117] for a case in Newfoundland, Canada. An analysis to determine the exactly suitable lines for DLR implementation was conducted in [118] also through modifying IEEE 14-bus test system via defining different climatic zones. The security preventive control oriented use of DLR from a different point of view was declared in [119] while the congestion management during network imbalance conditions was proposed to be handled through DLR using a probabilistic analysis in [120]. Many other generic studies for sole DLR implementation also exist in [121–127]. The taxonomy of the relevant aforementioned literature on solely DLR based flexibility integration in electric power system operation is presented in Table 2 with relevant categorization from different points of view.

Table 2. Taxonomy of the studies on solely DLR-based operational flexibility.

Ref.	Consideration Point of View	RES Availability	Problem Formulation Regarding Uncertainty	Implementation Level
[98–103,106–127]	Generic	-	Deterministic	Transmission
[104]	Generic	-	Robust	Transmission
[105]	Generic	-	Stochastic	Transmission
[79]	Generic	√ (Generic)	Deterministic	Transmission
[72]	Generic	√ (PV)	Deterministic	Distribution
[73–75]	Generic	√ (PV)	Deterministic	Transmission
[76]	Generic	√ (PV&Wind)	Deterministic	Distribution
[77,78]	Generic	√ (PV&Wind)	Deterministic	Transmission
[47,65]	Generic	√ (Wind)	Deterministic	Distribution
[42,46,48,49,57–59,63,64,66–69]	Generic	√ (Wind)	Deterministic	Transmission
[41]	Generic	√ (Wind)	Probabilistic	Distribution
[45,51–56,62]	Generic	√ (Wind)	Probabilistic	Transmission
[71]	Generic	√ (Wind)	Robust	Transmission
[43,44,50,60,61]	Generic	√ (Wind)	Stochastic	Transmission
[80–83,89,90]	Protection	-	Deterministic	Transmission
[84–88]	Protection	√ (Wind)	Deterministic	Transmission
[91–97]	Reliability	-	Deterministic	Transmission
[70]	Reliability	√ (Wind)	Deterministic	Transmission

3.2. Combination of DLR with Other Flexibility Options

The majority of the studies combining DLR with other flexibility options considered the possibility of transmission switching (TS) (and also a possible busbar splitting) or reconfiguration based network topology manipulation possibility respectively for enhanced transmission or distribution system operation. Among them, Jabarnejad and Valenzuela [128] combined DLR and TS based operational flexibility options in an operational constraints-integrated multi-stage long term planning problem formulated in a mixed-integer linear programming (MILP) based framework. The problem in [128], which can also be treated as a transmission expansion planning problem, was decomposed into a set of subproblems via Benders decomposition method, namely an energy excess and shortage minimization oriented feasibility problem, followed by cost minimization oriented optimal power flow and relaxed optimal power flow problems for feasible solutions of the feasibility subproblem, which in turn formed the optimality cuts to be added to the master problem in order to find the best lines to invest for DLR implementation combined also with TS possibility. The results obtained by case studies in two different test systems namely Garver's system (composed of 6 buses, 3 generator and 8 lines) and IEEE 118-bus system concluded that the integration of DLR with TS based flexibility further could decrease the overall operational and investment cost more than 10% compared to applying only DLR, which was even far more beneficial compared to SLR case with the selection of the most appropriate lines to apply DLR. Sheikh et al. [129] also considered the dual flexibility via TS and DLR where the reliability of circuit breakers affected by the number of switching operations for TS was also taken into account in a security-constrained stochastic unit commitment problem including an improved linear AC power flow model taking the scenarios regarding TS operation decisions as the source of uncertainty. The generation and load shedding- based costs minimization-oriented problem in [129] was decomposed into three levels via Benders decomposition as unit commitment as the master problem and security constraints and contingency evaluation as the subproblems. The tests on 6-bus and IEEE 118-bus test systems resulted in generation cost reduction reaching 8% and expected energy not supplied reduction more than 60% for the larger test system in [129]. Another study dealing with the incorporation of transmission network topology optimization (composed of TS and an additional busbar splitting approach) and DLR based flexibility into a day-ahead cost minimization-oriented network-constrained unit commitment model was proposed in [130]. The cost function in [130] was composed of generator dispatch (regarding generation, no-load, start-up and shut-down conditions), wind curtailment and load shedding based cost components and the case studies based tests conducted using modified IEEE RTS-79 system resulted in improved wind curtailment savings by slightly over 34%, 36% and 72%, dispatch cost savings by slightly over 16%, 10% and 19% respectively for cases considering only network topology optimization option, only DLR option and availability of both mentioned flexibility options compared to the base case with no flexibility. Other studies combining transmission system topology manipulation and DLR based flexibility options can be found in [131–134].

The dual reconfiguration and DLR based flexibility options were treated from a stochastic energy management point of view in [135] for a hybrid DC-AC microgrid including also RES units. The sources of uncertainty in operation within [135] were considered as the RES power generation, load demand, energy market prices as well as other DLR calculation related issues (wind speed, solar radiation, ambient temperature) for a cost (composed of cost components related to reconfiguration oriented switching operation, power generation by fuelled distributed generation units, energy purchase from upstream grid and ESS based power generation) minimization oriented linearized approach (it should be carefully noted here that even an ESS based cost component was added to the objective function, no other consideration was provided in other parts of the mentioned study regarding an ESS availability leading to disregarding the consideration of an ESS based flexibility in the scope of the mentioned study). The tests conducted on IEEE 33-bus test system modified by adding fuel cell and microturbines based fuelled distributed generation units, wind power based RES units in [135] resulted in an increase of operational total costs less than 1% (mostly related to the cost of reconfiguration oriented switching costs) but also a positive impact on grid security as the main declared consideration of the study.

There are also studies combining the flexibility of DLR option with different types of energy storage systems (ESSs)-based flexibility resources to enhance power system operation from different points of view. The benefits of joint flexibility options from both DLR and a battery based ESS for a wind power-dominated power system was considered from a load curtailment minimization-oriented reliability point of view by Teh and Lai in [136]. New wind power utilization-related reliability indices namely saved wind energy, supported wind energy and ability of wind farms for power supply participation were proposed in [136] using a DC power flow for case studies under different operational strategies conducted using IEEE 24-bus RTN sample system. Compared to the base case defined as no ESS or DLR availability in [136], it was found out that the ESS only case, DLR only case and joint ESS & DLR case decreased the well-known expected energy not supplied reliability indices respectively by 11.5%, 12.1% and 23.6%, and also several sensitivity analyses considering ESS parametric and operational policy impacts also resulted in different results in wind power related reliability indices. The study in [137] proposed a DLR-based flexibility for the tie line of a multi-area system including a further compressed air ESS-based flexibility under wind power generation availability. Combined economic and environmental issues based stochastic multi-objective problem aimed to minimize expected operational cost composed of conventional production, ESS employment and energy market-based cost components while also minimizing the emission function regarding the environmental impacts of conventional generation and ESS utilization. A hybrid simplicial decomposition, nonlinear block Gauss-Seidel and augmented Lagrangian methods based decomposition algorithm was implemented to decompose the general problem into subproblems and ε-constraint method based solution technique to form a Pareto front composed of multiple solutions and fuzzy satisfying method based best solution selection technique to determine the best solution were employed in [137]. The energy market prices and available percent of wind power based uncertainties were tackled via 12 scenarios, and the tests on 3-area and 5-area sample systems resulted in a slight decrement in wind spillage and operational costs as well as environmental impacts with only ESS availability but a significantly higher decrease in the mentioned operational issues reaching 10% with the implementation of both ESS and DLR based flexibility options.

The study presented by Martin and Hiskens in [138] proposed a model predictive control approach to minimize the deviation from economic dispatch for large power systems including RES and storage units. Even demand side flexibility was mentioned via demand response term in [138], it was treated more like a load shedding approach as a last resort to be used rather than a natural option to use in normal conditions and accordingly the demand side flexibility in state-of-the-art manner was not applied. The test case using the data of Californian transmission system composed of 4259 nodes and ten ESS devices (without mentioning the type but seems as a battery from the energy constraints based ESS model) corresponding to 0.5% of generation capacity were focused on implementation potential from computational and decision making performance points of view rather than a DLR or ESS based performance improvement comparison. Another study on joint ESS and DLR flexibility was proposed in [139] for resiliency improvement in distribution systems against wildfires. Both RES based (wind and solar systems) and fuelled distributed generation units, battery based ESS availability as well as operational uncertainties due to wind speed, wind direction, solar radiation and RES power production were considered in the proposed concept within [139]. The tests conducted using a modified version of IEEE 33-bus distribution test system for the social cost and load shedding minimization oriented stochastic approach in [139] were mainly focused on a comparison between the cases regarding the consideration of resiliency in the decision making process rather than the evaluation of the impacts of dual flexibility options. The benefits of combined ESS and DLR-based flexibility was further discussed in [140] from network reinforcement deferral point of view in a probabilistic manner.

The participation of demand side flexibility together with DLR in power system operation was also considered in some studies. Among them, a DSO experience from Belgium for considering the demand side flexibility as an active part of the distribution system operation rather than a last resort together with DLR was shared in [141] especially regarding congestion management in further wind power availability. Maximum demand side flexibility-oriented incentives were evaluated to make the use of demand side in the operation profitable in [141] together with the economic benefits obtained via DLR option. A probabilistic evaluation for optimal demand response scheduling, together with the DLR implementation in the day-ahead planning of transmission system operation was proposed in [142] and the use of a demand response program to enhance wind power utilization together with DLR existence was also considered in [143]. An interesting study to consider demand side flexibility via controlling the charging demand of electric vehicles was proposed in [144] aiming to minimize the total flexibility provision costs from generation and load sides as well as a penalty cost for transmission congestion regarding RES power curtailment. The tests on IEEE 14-bus system within [144] resulted in a decreased wind curtailment and dispatch cost with controlled electric vehicle charging when DLR was available.

The consideration of thermal ratings of other assets apart from OHLs or ULs as an additional flexibility option constitutes another group of studies for combined use of DLR. Among them, a day ahead dispatch optimization problem based on DC optimal power flow including the DLR of OHLs as well as dynamic rating of transformers was proposed in [145] for enhancing wind power integration. The results obtained in [145] using IEEE RTS-24 bus test system revealed a decrease of 0.1%, 0.5% and 11.4%, respectively, for the cases of considering only DLR of OHLs, only dynamic rating of transformers, and both DLR capability of OHLs and dynamic rating of transformers by enabling more integration of economic wind energy. The study of Yang et al. [146] even expanded the DLR concept to dynamic network ratings considering also ULs and transformers apart from OHLs for a distribution system to enable improving the utilization of all possible thermally sensitive assets in a real 11 kV distribution network based case study in Milton Keynes, UK. Another study in this manner combining the dual flexibility options from DLR and transformer thermal rating can also be found in [147] from post-contingency congestion avoidance point of view.

Apart from all, there are also studies dealing with other flexibility options combined with DLR. Among them, the combination of phase shifting transformers with DLR was proposed in [148], where the objective was to maximize available transfer capacity. The test in [148] using a 30-bus test system revealed an improvement of available transfer capacity reaching nearly 25%, 65% and 90% accordingly for the cases of considering only phase shifting transformer, only DLR, and joint phase shifting transformer and DLR based flexibility options compared to the condition of no flexibility option availability. There is a small number of studies (e.g., [149]) also combining the flexibility options provided by DLR and Flexible AC Transmission System (FACTS) equipment. There are also different studies combining more than two flexibility options (including DLR) in their concepts.

A similar group of authors presented in [135] a different version of the study in [150] including demand side (via shiftable loads as curtailable part declared in [150] was a load shedding approach not representing a state-of-the art demand side flexibility option as mentioned multiple times above) and battery ESS-based additional flexibility options apart from reconfiguration and DLR-based operational possibilities for the operational cost minimization oriented stochastic energy management of a microgrid. The cost component in [150] composed of reconfiguration-oriented switching costs, fuelled distributed generation costs, cost of purchased energy from upstream grid and battery ESS degradation costs, and the sources of uncertainty were determined as load demand, energy market price and RES power generation.

The taxonomy of the relevant aforementioned literature on combined flexibility options in power system operation including is presented in Table 3 also with relevant categorization from different points of view.

A final analysis on the trend evolution of DLR oriented literature studies for the last decade reveals the summarized results in Figure 2. It is obvious that the trend to combine DLR with other flexibility options gradually increases especially in the last five years. This is an important point to show that DLR has started to become a more utilized option for system operators and the mentioned system operators try to harvest all types of flexibility resources they may use to enhance the power system operation.

Table 3. Taxonomy of the studies on combination of DLR with other flexibility options.

Ref.	**The State-of-the-Art Flexibility Option Apart from DLR (Neglecting Mature Conventional Generation Based Production Side and Load Shedding Based Demand Side Flexibility Options)**						**RES Availability**	**Problem Formulation Regarding Uncertainty (and Considered Source(s) of Uncertainty if Possible)**	**Implementation Level**	**Main Results/Findings**
	Network Topology Manipulation			**Demand Side Flexibility**	**Energy Storage System (and the Storage System Type if Possible)**	**Other (and Flexibility Option if Possible)**				
	TS	**Reconfiguration**	**Busbar Splitting/ Switching**							
[128]	√	-	-	-	-	-	√	Deterministic	Transmission	The results obtained by case studies in two different test systems namely Garver's system (composed of 6 buses, 3 generator and 8 lines) and IEEE 118-bus system concluded that the integration of DLR with TS based flexibility further could decrease the overall operational and investment cost more than 10% compared to applying only DLR, which was even far more beneficial compared to SLR case with the selection of the most appropriate lines to apply DLR.
[129]	√	-	-	-	-	-	-	Probabilistic (TS operation decisions)	Transmission	The tests on 6-bus and IEEE 118-bus test systems resulted in generation cost reduction reaching 8% and expected energy not supplied reduction more than 60% for the larger test system
[130]	√	-	√	-	-	-	√	Deterministic	Transmission	The case studies based tests conducted using modified IEEE RTS-79 system resulted in improved wind curtailment savings by slightly over 34%, 36% and 72%, dispatch cost savings by slightly over 16%, 10% and 19% respectively for cases considering only network topology optimization option, only DLR option and availability of both mentioned flexibility options compared to the base case.
[131]	√	-	√	-	-	-	-	Deterministic	Transmission	The tests conducted using IEEE 79-bus and 96-bus sample system resulted in a decrease in the Loss of Load Expectation and Expected Energy not Served reliability indices from 56% to 7% with the implementation of DLR compared to base case.
[132]	√	-	-	-	-	-	-	Deterministic	Transmission	The tests conducted using IEEE 79-bus resulted in a load curtailment value of 88.60 MW, 4.54 MW, and 0 MW respectively for the base case, only DLR case and combined DLR and TS case.

Table 3. *Cont.*

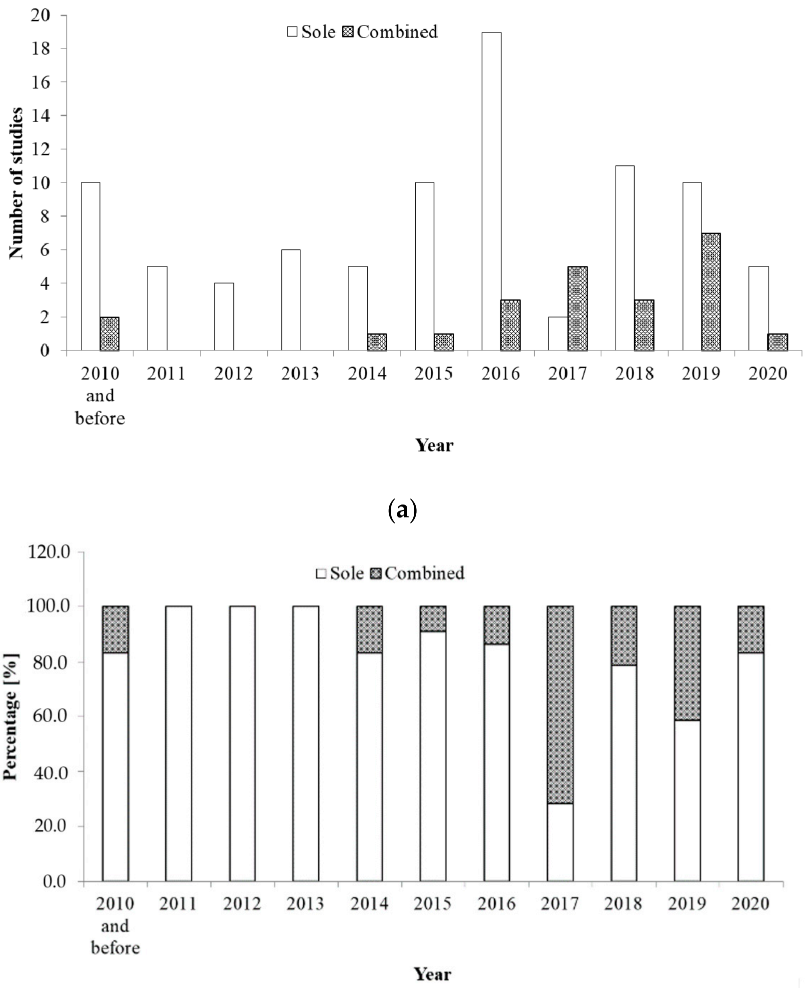
Ref.	The State-of-the-Art Flexibility Option Apart from DLR (Neglecting Mature Conventional Generation Based Production Side and Load Shedding Based Demand Side Flexibility Options)						RES Availability	Problem Formulation Regarding Uncertainty (and Considered Source(s) of Uncertainty if Possible)	Implementation Level	Main Results/Findings
	Network Topology Manipulation			Demand Side Flexibility	Energy Storage System (and the Storage System Type if Possible)	Other (and Flexibility Option if Possible)				
	TS	Reconfiguration	Busbar Splitting/ Switching							
[133]	√	-	-	-	-	-	√	Deterministic	Transmission	The tests conducted using IEEE 79-bus resulted in a dispatch cost saving of 11.69%, 19.12% and 28.71%, and wind curtailment saving of 30.79%, 38.86% and 70.10% respectively for only TS, only DLR and combined TS and DLR cases compared to base case.
[134]	√	-	-	-	-	-	-	Deterministic	Transmission	Implementation of TS in addition to DLR resulted in the decrease of line loading differences from 87% to 58%.
[135]	-	√	-	-	-	-	√	Stochastic (RES power generation, load demand, energy market prices as well as other DLR calculation related issues (wind speed, solar radiation, ambient temperature)	Microgrid	The tests conducted on IEEE 33-bus test system modified by adding fuel cell and microturbines based fuelled distributed generation units, wind power based RES units resulted in an increase of operational total costs less than 1% (mostly related to the cost of reconfiguration oriented switching costs) but also a positive impact on grid security as the main declared consideration of the study.
[136]	-	-	-	-	√ (battery)	-	√	Deterministic	Transmission	In the case studies conducted using IEEE 24-bus RTN sample system, it was found out that the ESS only case, DLR only case and joint ESS&DLR case decreased the well-known expected energy not supplied reliability indices respectively by 11.5%, 12.1% and 23.6% compared to the base case defined as no ESS or DLR availability.
[137]	-	-	-	-	√ (compressed air energy storage)	-	√	Stochastic (energy market prices&available percent of wind power)	Transmission	The tests on 3-area and 5-area sample systems resulted in a slight decrement in wind spillage and operational costs as well as environmental impacts with only ESS availability but a significantly higher decrease in the mentioned operational issues reaching 10% with the implementation of both ESS and DLR based flexibility options.
[138]	-	-	-	-	√ (not specified)	-	√	- (Real-time control)	Transmission	The test case using the data of Californian transmission system composed of 4259 nodes and ten ESS devices (without mentioning the type but seems as a battery from the energy constraints based ESS model) corresponding to 0.5% of generation capacity were focused on implementation potential from computational and decision making performance points of view rather than a DLR or ESS based performance improvement comparison.

Table 3. *Cont.*

Ref.	The State-of-the-Art Flexibility Option Apart from DLR (Neglecting Mature Conventional Generation Based Production Side and Load Shedding Based Demand Side Flexibility Options)						RES Availability	Problem Formulation Regarding Uncertainty (and Considered Source(s) of Uncertainty if Possible)	Implementation Level	Main Results/Findings
	Network Topology Manipulation			Demand Side Flexibility	Energy Storage System (and the Storage System Type if Possible)	Other (and Flexibility Option if Possible)				
	TS	Reconfiguration	Busbar Splitting/ Switching							
[139]	-	-	-	-	√ (battery)	-	√	Stochastic (wind speed, wind direction, solar radiation, RES power generation)	Distribution	The tests conducted using a modified version of IEEE 33-bus distribution test system for the social cost and load shedding minimization oriented stochastic approach were mainly focused on a comparison between the cases regarding the consideration of resiliency in the decision making process rather than the evaluation of the impacts of dual flexibility options.
[140]	-	-	-	-	√ (battery)	-	-	Probabilistic (load demand)	Distribution	The study results mainly depicted how sensitive the battery sizing were to the application of DLR.
[141]	-	-	-	√	-	-	√	Deterministic	Distribution	The load curtailment values were significantly affected by the implied different flexibility options including DLR.
[144]	-	-	-	√	-	-	√	Deterministic	Transmission	The tests in IEEE 14-bus sample system revealed to a decrease of 40% in operational costs for the case of combined flexibility options compared to base case.
[142]	-	-	-	√	-	-	√	Probabilistic (customer availability for demand response)	Transmission	The results obtained using IEEE 96-bus test system revealed a decrease of 61% and 6.6% when DLR and DR were used together respectively compared to DR only and DLR only cases.
[143]	-	-	-	√	-	-	√	Deterministic	Transmission	The wind curtailment decreased from 133 MW to 67 MW and 10.9 MW respectively for the cases of only DR and combined DR and DLR cased compared to base case with no flexibility.
[146]	-	-	-	-	-	√ (transformer dynamic thermal rating)	-	Deterministic	Distribution	The results of FALCON project in UK were shared in terms of the effect of different operating and ambient conditions on the dynamic limits of thermally-constrained assets.
[145]	-	-	-	-	-	√ (transformer dynamic thermal rating)	√	Deterministic	Transmission	The results obtained using IEEE RTS-24 bus test system revealed a decrease of 0.1%, 0.5% and 11.4% respectively for the cases of considering only DLR of OHLs, only dynamic rating of transformers, and both DLR capability of OHLs and dynamic rating of transformers by enabling more integration of economic wind energy.

Table 3. *Cont.*

Ref.	The State-of-the-Art Flexibility Option Apart from DLR (Neglecting Mature Conventional Generation Based Production Side and Load Shedding Based Demand Side Flexibility Options)						RES Availability	Problem Formulation Regarding Uncertainty (and Considered Source(s) of Uncertainty if Possible)	Implementation Level	Main Results/Findings
	Network Topology Manipulation			Demand Side Flexibility	Energy Storage System (and the Storage System Type if Possible)	Other (and Flexibility Option if Possible)				
	TS	Reconfiguration	Busbar Splitting/ Switching							
[147]	-	-	-	-	-	√ (transformer dynamic thermal rating)	-	Deterministic	Transmission	Several generator re-dispatch cost and load shedding results were shared without further comparisons with a base case.
[148]	-	-	-	√	-	√ (phase shifting transformer)	-	Deterministic	Transmission	The test realized using a 30-bus test system revealed an improvement of available transfer capacity reaching nearly 25%, 65% and 90% accordingly for the cases of considering only phase shifting transformer, only DLR, and joint phase shifting transformer and DLR based flexibility options compared to the condition of no flexibility option availability.
[149]	-	-	-	-	-	√ (FACTS)	√	Deterministic	Transmission	The combined flexibility options increased the system available transfer capacity by 33.5% for a case study conducted using IEEE 39-bus test system.
[150]	-	√	-	√	√ (battery)	-	√	Stochastic (load demand, energy market price, RES power generation)	Microgrid	Even each flexibility option affected system performance and economy, the DLR was found to be one of the most dominant flexibility solution.



(**a**)

(**b**)

Figure 2. The representation of the trend evolution regarding DLR oriented literature studies: (**a**) Variation of total number of studies from "sole" and "combined" flexibility perspectives, (**b**) The percentage of "sole" and "combined" flexibility perspectives in the relevant periods.

4. Conclusions

Even the pioneering studies on DLR based flexibility go back to more than a half century; the mentioned concept has regained vital attention especially in the last decade regarding the attempts on the smartification of power system operation. There are multiple stages for DLR concept evaluation from implementation to operationally utilization of DLR solutions. Therefore, the DLR has different points-of-view to consider for a wider adaptation of such a flexibility option in the power system. In this manner, this study mainly focused on the overview of the use of DLR based flexibility in the power system operation from different categories regarding sole or combined usage of DLR in the overall power system decision making procedure. Initially, brief background information together with a geographically categorized presentation of the practical evidence was also supplied. The mentioned practical evidence-based analysis clearly showed that the America and Europe continents have passed a considerably longer way in DLR implementation while the applications in other continents can still be considered as premature but promising. The enabling technologies have also been evolving well recently that will enhance these practical applications.

Afterwards, a very detailed literature analysis with relevant categorization attempts was provided. In this manner, this was the first study reviewing the existing studies mainly on operational perspective rather than many existing studies on implementation category of DLR solutions. The distinction between the use of the DLR in a sole or combined way as a flexibility option was also assessed as a further vital categorization. A trend analysis was also conducted on the tendency of the literature for using DLR either as a sole flexibility option or in a combined way with other flexibility options. It can then clearly be concluded from this analysis that double or even more flexibility options including DLR will have a more increasing area of use in the near future together with the parallel interest from the industry supporting this growth.

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