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Research and application of dynamic line rating technology

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Abstract

Dynamic line rating is a technology that can be used to improve the transmission efficiency and capacity of the existing power system without changing the system structure or breaking the current technical specification. It is an economical and feasible method to meet the increasing power demands and the needs for new energy integration. In order to ensure the safe and stable operation of power system, the specific technologies and application methods affecting the reliability of DLR are discussed. The main limitations of data acquisition technology of transmission lines are analyzed, the advantages and disadvantages of different perception analysis methods are classified, several application architectures of the DLR system are compared, and some applications of current DLR technologies in actual engineering are discussed. The problems existed in the technologies of DLR are pointed out from four aspects: data acquisition, perception analysis, application architecture, and engineering practice, such as the quality of data acquisition is low, the dependence of perceptual analysis on parameters and the data collected is high, the application architecture is open-loop, the analysis on the overall security of the power grid is deficient. Finally, the future research direction is pointed out.

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Keywords: Transmission line; Dynamic line rating; Data acquisition; Perception analysis; Application architecture; Reliability

1. Introduction

Transmission lines are efficient and fast energy transmission channels and a key link for the safe operation of the power grid. With the rapid increase in electricity demand and the integration of a large amount of renewable energy, improving the transmission capacity of the power system has been an important issue to be solved [1–3]. Considering the fluctuation of the load curve and the intermittency of renewable energy, there is no need for the capacity-increase system of transmission lines to operate the whole time [4]. Improving the transmission capacity of the power grid through the construction of new transmission lines not only has a long period and a large investment but also brings environmental pollution. The technology of dynamic line rating (DLR) [5–7] can significantly improve the

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transmission capacity of transmission lines, alleviate transmission line congestion, and integrate renewable energy, therefore the application prospect of DLR technology is great.

The DLR technology can obtain the maximum current carrying capacity of transmission lines according to the DLR model by collecting or predicting the line environment and conductor status information, and improve the transmission efficiency and capacity of the transmission system without breaking the current technical regulations. At present, the technology of DLR has been widely studied [8,9]. However, affected by sensor technologies, communication methods, DLR models, system architecture, and many other factors, the reliability of the results of DLR systems is not high. It is difficult to ensure the safe and stable operation of the power grid during the process of dynamic capacity increase, and the DLR technology has not been widely used in actual power system engineering.

In this paper, the key factors affecting the reliability of DLR technology is analyzed in detail from the aspects of data acquisition technology, perception analysis technology, system application architecture, and engineering practice. The limitations of current research on DLR technology are summarized and the future research direction is pointed out.

2. Data acquisition technology of transmission lines

The realization of DLR technology relies on the acquisition of key status information of transmission lines, including environmental information and conductor status information, such as ambient temperature, sunshine intensity, wind speed and direction, conductor temperature, conductor sag, etc. Various types of status monitoring devices installed on the transmission line collect real-time transmission line environment and conductor status information, and then send the collected data to the data center for processing and displaying through data communication technology [10,11].

The existing transmission line data acquisition technology research is relatively mature, but there are still many shortcomings that limit the quality of transmission line data collected, mainly summarized as the following aspects:

(1) Problems with sensors

As the most widely used sensing element, the sensor has the advantages of convenient installation, relatively high acquisition accuracy, and relatively simple method of use, which is widely used in data acquisition of transmission lines. However, since the transmission lines are usually set up outdoors, the working environment is relatively harsh, and there is strong electromagnetic interference around the high-voltage transmission lines, which seriously affects the data acquisition and transmission quality of the transmission lines. The online operation efficiency of equipment installed on the existing transmission lines is less than 40%, which is difficult to meet the reliability requirements of data acquisition.

The principle and installation process of the sensor will also bring some monitoring errors. Take the temperature sensor as an example. Contact temperature sensors such as optical fiber temperature sensors [12] are directly installed on the surface of the lines, which have relatively high measurement accuracy, but the operation risk is also relatively high. The batteries and other energy storage units of the sensors installed in the high-voltage transmission lines have safety hazards, and the line insulation is easily worn by contact sensors when the line wobbles. Non-contact sensors such as infrared temperature sensors [13] do not contact with transmission line directly, so the use of them is relatively convenient and safe. But the measurement results are related to the surface cleanliness of the wire and vulnerable to environmental factors, so the measurement accuracy is insufficient. Usually, the temperature sensor can only monitor the surface temperature of the wire, whereas the wire often has a radial temperature difference of 4–10 °C, which can affect the current carrying capacity of the transmission line by more than 10% [14].

Generally, the function of the sensor is single, and the specific type of sensor can only realize the measurement of a specific state. Therefore, it is necessary to install new types of sensors and corresponding background software to obtain the new type of monitoring data, which will cause repeated construction and investment, increase maintenance workload, and reduce system reliability. The information exchanges between different manufacturers and different devices are difficult and have poor compatibility, which will greatly limit the effectiveness of the data acquisition system.

(2) Problems with communication methods

Traditional transmission line communication mostly uses a wireless public network [11], and the communication modes mainly include general packet radio service (GPRS), code division multiple access (CDMA), and 3G. The wireless public network communication technology is relatively mature, simple deployment, low construction cost,

Table 1. Comparison of several common communication methods on transmission lines.

Communication technology	Transmission distance	Bandwidth	Power consumption	Networking	Cost
ZigBee	<300 m	250 kbps	low	Ad hoc	low
BlueTooth	<100 m	1–2 Mkbps	low	Ad hoc	low
LoRa	15 km in suburbs, 1–2 km in urban areas	0.3–50 kbps	low	Ad hoc	low
NB-IoT	15 km	250 kbps	low	Carrier cellular network	low
Microwave	5–20 km	10–100 Mbps	high	Ad hoc	high

but its coverage is limited, communication is vulnerable to be disturbed, and the security and reliability of it are low. When the communication system breaks down, it is difficult to be repaired quickly and cannot guarantee the reliable transmission of the data collected.

With the rapid development of communication technology, Zigbee, BlueTooth, LoRa, NB-IoT, microwave, and other wireless communication technologies have been applied in transmission line communication [15]. The performance of several commonly used wireless communication technologies was tested, and the results are shown in Table 1.

Among them, it is difficult for ZigBee or BlueTooth to meet the transmission line communication needs for the reason that the communication distance of them is limited. LoRa and NB-IoT can realize small-range narrow-bandwidth communication of transmission lines, but it is difficult to meet the real-time requirements of image and video information transmission. The networking of NB-IoT is based on the operator's cellular network, and the signal coverage is limited, therefore the establishment of the base station is needed. Microwave communication can meet the needs of wide bandwidth data transmission such as video and images, but the communication power consumption of it is relatively high, which places high requirements on the stable power supply capability of the communication devices. In addition, the strong electromagnetic interference of high-voltage transmission lines will also have a bad effect on the communication equipment and wireless communication quality.

(3) Problems with equipment power supply

Both transmission line data acquisition and communication equipment require a stable and reliable power supply to ensure the normal operation of the system. However, due to the special operating environment of transmission line on-line monitoring devices, the reliability of the power supply of those devices is greatly challenged.

In the existing transmission line system, the monitoring equipment installed on the tower is mostly powered by solar energy and battery, and the equipment on the line is mostly powered by a high-voltage transformer combined with lithium battery [16] and super capacitor [17]. These power supply methods can solve the power supply problem of transmission line monitoring equipment basically, but they are greatly affected by the external environment. It will bring reliability problems of power supply in many cases such as continuous rainy days, solar panel pollution, low line load, or low operating temperature, which in turn affect the quality of data acquisition and transmission.

Limited by the installation environment, the volume of the transmission line acquisition and communication devices installed on the top of the line or tower is limited. The size of a single solar panel installed on a tower of the line shall not exceed 0.8 m×0.7 m, and the weight of a single power supply device shall not exceed 35 kg. The weight of a contact wire monitoring device should be less than 2.5 kg. There is a lake of a safe and effective power supply method, usually only use a small-capacity battery for power supplies, which limits the bandwidth and frequency of data acquisition and transmission. Due to the limitation of battery capacity, the monitoring and communication equipment of transmission lines usually have a service life of only 6–8 years, resulting in difficulties in equipment replacement and maintenance.

(4) Other problems

In addition to the power supply by sensors and communication methods, the reliability of data acquisition on the transmission line is also affected by factors such as the monitored objects and installation locations. For example, micro-meteorological information is usually difficult to measure, and the wind speed and direction of the line change rapidly. When the wind speed is less than 1 m/s, the measurement results of the wind speed and wind direction usually have large errors. Sunlight intensity will also be affected by topography and obstacles, such as the movement of clouds that may cause rapid changes in sunlight intensity. Besides, the differences in terrain, line orientation, and local meteorological conditions lead to a great difference in the operating environment of each span of the line. The measurement of the local state often cannot reflect the overall situation of the transmission line.

In view of the poor quality of transmission line data acquisition, most of the existing researches improves the reliability of data acquisition by using high-precision data acquisition equipment, increasing the type and number of data acquisition devices, increasing the collection density, and enhancing the communication ability of transmission lines. For example, self-power supply technology of sensors [18], passive fiber grating sensors [19,20] and surface acoustic wave sensors [21] are researched to solve the problems of unreliable equipment power supplies and poor anti-interference ability of traditional sensors. The type and number of sensors are increased and the installation location of the monitoring device is optimized to improve the capability of data acquisition [22,23]. Various wireless communication technologies, such as WiFi, Mesh, ZigBee, etc. are combined with fiber-optic wired communication to form hybrid communication networks [24–27] to improve the communication capability of transmission lines and the private networks of transmission lines are planned to be built to replace public networks. The data acquisition and communication ability of transmission lines can be improved by these methods to a certain extent, but often a significant increase in acquisition costs will also be caused. For example, the error caused by local measurement can be reduced by improving the precision and quantity of transmission line sensors, but there will be a significant increase in equipment cost, maintenance cost, and the burden of communication system, whereas the problems of low sensor on-line rate and false alarm are still difficult not be solved.

Increasing the types and quantity of monitoring devices and improving the line communication ability cannot solve the problem of data acquisition quality completely. Instead, we should focus on the key problems of data acquisition, including equipment power supplies, ad hoc communication, equipment on-line rate, and other issues, continuously improve the effective data acquisition capacity on the basics of existing micropower consumption equipment and the main network communication system.

3. Perceptual analysis technology of transmission lines

Transmission line perception analysis technology firstly needs to process and identify the environment and conductor information obtained by the data center to ensure the normal operation of the DLR system when the collected data is not comprehensive or the quality is not high, mainly including missing data supplement, abnormal data correction, and normal sampling data integration protocol, etc. The preprocessed data is used to obtain information such as current carrying capacity, conductor temperature, and conductor sag through the DLR model of the transmission line.

The existing transmission line DLR models are mainly divided into the deterministic model and the probabilistic model, as shown in Fig. 1.

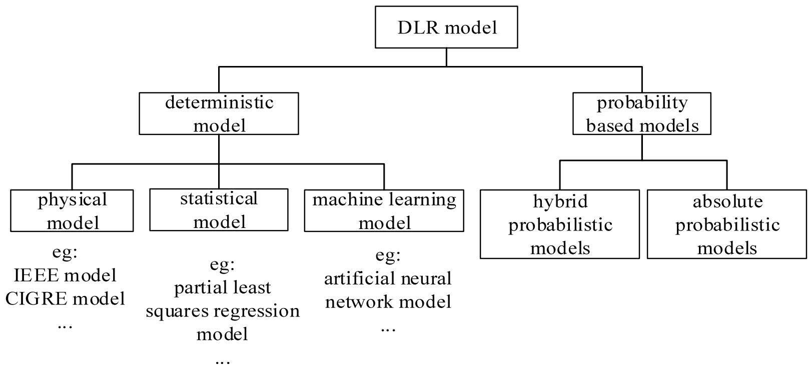


Fig. 1. Classification of DLR model.

The output of the deterministic model is obtained by a set of inputs through the deterministic relationship, without any random factors. In the final deterministic model, the output is always the same for a given set of inputs [28]. Deterministic models can be divided into physical models, statistical models, and machine learning models according to different analysis methods.

The construction of the physical model is mainly based on the steady-state heat balance equation, Eq. (1) [29] and the transient heat balance equation Eq. (2) [30] of the transmission line, typical of which is the IEEE model [31], CIGRE model [32] and IEC model [33]. I is the current carrying capacity; $R(T_c)$ is the conductor AC resistance at temperature T_c; Q_s is the solar thermal absorption power of conductor; Q_c is the convective thermal dissipation power of the conductor; Q_r is the radiant thermal dissipation power of conductor; M is the mass per unit length of conductor; C_p is the combined heat capacity coefficient of conductor.

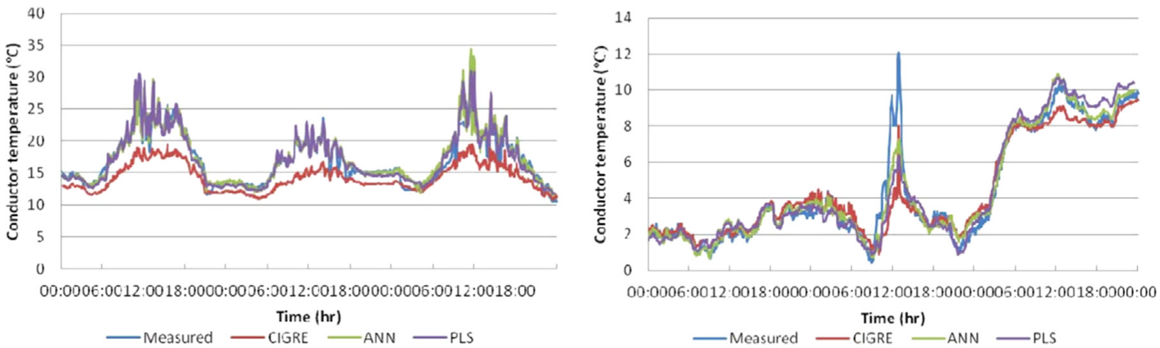
$$I^2R(T_c) + Q_s = Q_c + Q_r \tag{1}$$

$$\frac{dT_c}{dt} = \frac{Q_s + I^2R(T_c) - (Q_c + Q_r)}{MC_p} \tag{2}$$

The principle of the physical model is simple, and it can be calculated or predicted in real-time according to the input parameters, but it is difficult to cover all the influencing factors of the line, such as the impact of rainfall on the cool effect. Some parameters in the physical model are difficult to obtain accurately. For example, the radiation coefficient and heat absorption coefficient are related to the old and new degree of the wire and the pollution degree of the wire surface, and the values of them are often based on empirical judgment. One way to improve the physical model is to supplement it by considering neglected influencing factors in the model, such as the extended CIGRE model that takes the cooling effect of precipitation into account [3,34].

In the statistical model, the partial least squares regression technique is usually used for the DLR model due to its good predictive ability [35,36]. The partial least square regression (PLSR) method is usually used to fit the relationship between the conductor temperature and the environmental factors and the conductor current. In the statistical model, the fitting function can be optimized according to physical relations, for example, conductor temperature is more directly related to the square of the current, whereas the effect of forced convection is a function of the product of wind speed and the sine of direction angle [37]. To some extent, the statistical model alleviates the problems of incomplete consideration of physical model and inaccurate parameters, but it needs a large number of outage experimental data for fitting. At the same time, the relationship fitted can only be used for the specific location of the line, and the other lines need to be refitted.

Machine learning models also require large amounts of experimental data for model training, such as artificial neural network (ANN) models. All available data will be divided into three groups for training, validation, and testing of the model. Unlike the partial least square method in statistical models, the trained neural network no longer uses linear relationship for fitting, but generates weights for each input parameter, and collects all responses of each input into the hidden layer to generate model output. The machine learning model does not depend on the specific parameters of the system and avoids the influence of neglected factors, but the versatility of the model requires the support of a large amount of training data from multiple sampling points on the line. Such a large amount of experimental training data is usually difficult to obtain in actual engineering.



(a) Summer (b) Winter

Fig. 2. Conductor temperature curve of the transmission line.

Fig. 2 shows the comparison between the measured temperature of a transmission line conductor and the perception results of three deterministic models under two typical experimental scenarios in summer (a) and winter (b) [38]. It can be seen that the ANN model and the PLSR model can better reflect the actual situation of the line.

Table 2. Comparison of different kinds of DLR models.

Model types		Model features	Modeling methods	Advantages	Disadvantages	Examples
Deterministic model	Physical model	The output is obtained by the input through deterministic relation without any random factors	Based on the heat balance equations;	The physical meaning is clear; the implementation is simple; the versatility is strong;	Ignore certain influencing factors; specific parameters of the model are difficult to obtain accurately;	IEEE model; CIGRE model; IEC model;
	Statistical model		Based on data fitting;	Avoid the problem of incomplete factors and inaccurate parameters;	Only applicable to specific lines; need a large amount of power outage data for fitting; sensitive to abnormal data;	PLSR model
	Machine learning model		Based on model training;	Avoid the problem of incomplete factors and inaccurate parameters;	Only applicable to specific lines; need a large amount of power outage data for model training; need to retrain the model when wrong data occurs;	ANN model
Probability-based model	Hybrid probability model	The inputs and outputs are not specific values, but rather data distributions	Based on probability function;	Reduce the impact of inaccurate environment and line information; introduce risk factors to characterize the potential risk factors;	Probability-based prediction requires a lot of statistical data; building and solving probability models is more complicated; the stability of probability models is poor;	Probabilistic model combined with Monte Carlo
	Absolute probability model					

The probability model is based on probability functions, and its input and output are not a specific set of values, but a set of data distributions, so as to provide more accurate information about environment and load conditions [39,40]. Risk factors can be introduced in the probabilistic model to characterize the potential risk factors in each case, thus providing a reference for the dispatcher's decision [41,42]. There are two types of DLR probability models: hybrid probability model and absolute probability model. The hybrid probability model combines the characteristics of the physical model and the probability model. Its discrete input is combined with distribution function, and its risk coefficient often does not include various external factors, so it can only represent a relative risk. The absolute probability model considers external factors such as lightning strike risk, and its risk coefficient usually represents absolute risk [28].

Table 2 gives a comparison of the above models. Among them, the physical model is simple to implement and versatile, but the accuracy of it is relatively low; the accuracy of the statistical model and machine learning model is high, but these models require a large amount of power outage experimental data to fit or train the models, and the models' versatility is limited; the probability model can represent the risk of each case by introducing risk factors, but it needs a large number of statistical data for supporting, and the stability of the model is poor. Therefore, the reliability of the DLR model of transmission lines depends on factors such as model accuracy, applicability, and stability.

Through real-time data acquisition and perception analysis, the real-time maximum current carrying capacity of the transmission line can be obtained. However, if the grid is controlled only based on the real-time maximum current carrying capacity of the line, when the system operating conditions or climatic conditions deteriorate, it is inevitable that the line will be overloaded. Therefore, it is necessary to predict and analyze the future short-term dynamic maximum current carrying capacity of the line. The DLR model is usually combined with the weather prediction model to predict the future short-term maximum current carrying capacity of the transmission line [42]. The existing transmission line weather prediction technologies mainly adopt the method of time series analysis [4,41] or numerical weather forecast [4,43,44]. Zhang et al. [41] applied Bayesian time series technology to the dynamic maximum current carrying capacity prediction of transmission lines, but the prediction error of this method increases with the increase of prediction time and is only applicable to the prediction within a few hours. Aznarte and Siebert [43] proposed a new dynamic maximum current carrying capacity prediction method for transmission lines by using numerical weather prediction and machine learning, which can achieve 1–2 days dynamic maximum current carrying capacity prediction, but its huge calculation needs to rely on a large calculator. In addition, Molinar et al. [45] used the quantile regression forest to achieve an accurate prediction of dynamic line current capacity within two days. A current capacity prediction model of transmission lines based on the Echo State Network (ESN) was proposed by Yang et al. [46]. Fuzzy analysis methods were introduced into the process of dynamic line current capacity prediction by Madadi et al. [47].

4. Application architecture of DLR system

In addition to the data acquisition technology and perception analysis technology of transmission lines, the inadequacy of the design of the application architecture will also indirectly affect the reliability of DLR technology. DLR systems usually include condition monitoring device (CMD), condition monitoring agent (CMA), and master station system. According to different data acquisition technology, communication mode, system function, and specific implementation methods, there are various application architectures [8,48–50].

Huang [48] of Xi'an Polytechnic University proposed a DLR system based on wireless temperature sensors, the architecture of it is shown in Fig. 3. The states of transmission lines and environment information are collected by the meteorological sensors on the tower and the wireless temperature sensors on the line in a real-time or fixed time. The data collected is sent to the aggregation node on the tower through ZigBee for packaging, and then transmitted to CMA through GSM/GPRS/CDMA/3G/WiFi/optical fiber, and then sent to the condition information acquisition gateway(CAG) through the CMA to achieve data interaction with the master station control system [49]. The dynamic capacity limit of the transmission line is calculated by expert software, and the data from the SCADA system and the temperature/sag security criterion is used to guide the dynamic capacity increase of transmission line.

Zhou et al. [50] of NARI group corporation has developed an online monitoring DLR system based on 3G/GSM, the architecture of it is shown in Fig. 4. The environment and wire information collected by sensors is sent to CMA in real-time through GPRS/3G. Then the CMA converts the data license of the acquisition terminal and sends it to

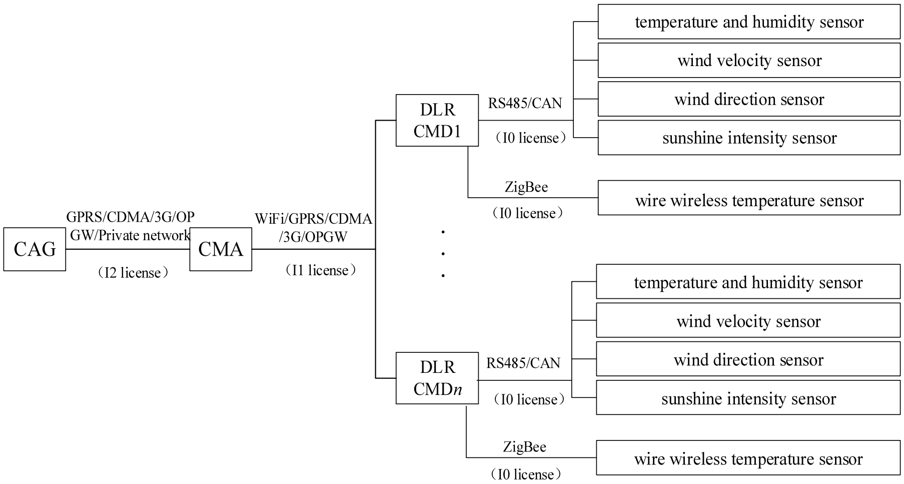


Fig. 3. The architecture of the DLR system based on the wireless temperature sensor.

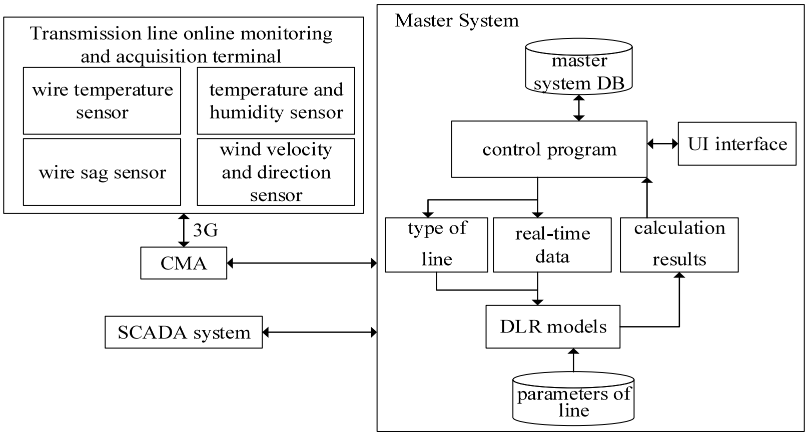


Fig. 4. The architecture of transmission line dynamic capacity increase system based on 3G/GSM.

the master station system. The real-time dynamic limit of the transmission line is calculated by DLR models in the master station system, and then the hidden capacity of the line can be obtained by comparing the dynamic limit with the current of the SCADA system. The DLR system has been applied in the Haminan-Zhengzhou ±800 kV DC transmission project, and the operation effect is good.

The above DLR systems only analyze a single transmission line and lack the overall dispatch planning of the power grid during the dynamic capacity increase process. It is difficult to analyze the impact of single or multiple line capacity increases on other transmission lines. The safe and reliable dynamic capacity increase of a single line may cause an overload of other associated lines.

Considering the characteristics and requirements of the power grid regulation, Wang et al. [8] analyzed the DLR technology from the grid level, and proposes a DLR system considering the static security of the power grid, as shown in Fig. 5. This system mainly includes four parts: data processing, real-time calculation, capacity increase analysis, and graphic visualization. The data processing unit is responsible for processing and identifying the collected/predicted data, integrating available data and identifying, and correcting erroneous data to improve data accuracy. The real-time calculation unit calculates the current carrying capacity information and dynamic power limit of the transmission line by thermal stability equation of transmission line, and the results are used to evaluate the static security of the power grid during the dynamic capacity increase process. The graphic visualization unit displays the results of the real-time calculation, and upload the data of the local dispatching system to the provincial

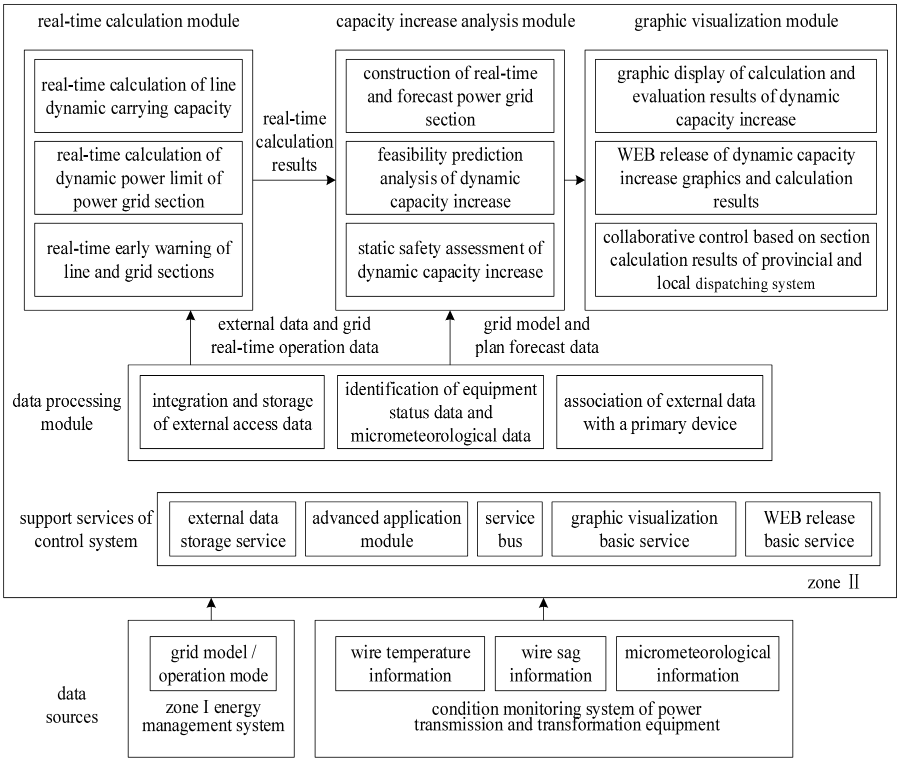


Fig. 5. The architecture of transmission line dynamic capacity increase system based on grid regulation.

dispatching system for the coordination control of the dynamic capacity increase. This DLR system has been applied in the D5000 system in Nanjing.

At present, some researches have been carried out to guide the dynamic capacity increase of the power grid from the overall dispatch planning level. For example, an overall implementation scheme together with the function module designs was proposed in the power grid dispatch and control system to apply the DLR technology to the grid analysis level [8]. A new dynamic capacity-increase method based on congestion management analysis was proposed by Xu et al. [9], the reasons for transmission capability restriction are clarified based on ultra-short-term forecasting data, and the key transmission lines are identified by congestion management analysis considering dynamic security constraints. In addition, some scholars have studied the risk assessment methods of DLR technology to evaluate the effect of capacity changes on line reliability. For example, Dupin et al. [51] proposed a forecast model for a day-ahead real-time thermal rating, and a forecast-based post-contingency risk assessment methodology is developed. Ying et al. [52] proposed a new thermal circuit model that considers pulsating characteristics of parameters, and the risk of dynamic overhead lines rating is controlled in a rational range by estimating ampacity in the form of probability. Markov chain Monte Carlo (MCMC) was used to assess the operational risk of transmission line using DLR technology [53,54], and the operation risk indices of transmission line are calculated [53]. However, most of these risk assessments are only for the operation of a single line, and there is a lack of research on the method to evaluate the operation risk of capacity increase from the grid level [55,56]. The safe and reliable dynamic capacity increase of a single line may result in overloads of other associated lines. At the same time, the security check method is not perfect. Usually, only the temperature and sag security criteria are considered, lacking the analysis on the safety and stability of the system in the event of failures, such as the N-1 accident [57].

In addition, the architecture of existing DLR systems is mostly open-loop. These DLR systems often simply use the real-time acquisition data or prediction data of the line to obtain the real-time/prediction maximum current carrying capacity of the line through the DLR model to guide the increase of transmission line current capacity. There is no closed-loop verification of the data and calculation model. It is difficult to guarantee the reliability of the result of DLR systems when the input data or model has large errors.

In a DLR system, the analysis should not be based on complete confidence in the collected data, nor should the application be based solely on the results of the perceptual analysis, but multiple redundant and multidimensional fault tolerance judgments should be introduced to build a closed-loop DLR system architecture. In the process of dynamic capacity increase, it is necessary to comprehensively consider the influence of power generation plan, maintenance plans, load forecast and other factors from the grid level, consider the static security of the grid, and carry out a risk assessment for the capacity increased lines, so as to ensure the safety and reliability of the dynamic capacity increase of the transmission lines.

5. Engineering application of DLR technology

In recent years, due to the shortage of transmission corridors and the increasing demand for integration of wind power, photovoltaics, and other new energy, the DLR technology has been applied in some developed countries and regions such as the United States and Europe as an effective way to support the efficient operation of transmission lines [58–60]. In addition, there are some demonstration application projects in China southern power grid and state grid [61].

A British research institute applied DLR technology on a 132 kV line between Skegness and Boston to improve the flexibility of power system operation [62]. The SRP(Salt River Project) company of the United States used DLR technology on two transmission lines to make the capacity temporarily exceed the static rating during peak load period, delaying the construction of new transmission lines and reducing the investment cost of about 9 million dollars [59]. The CAT-1 transmission line capacity dynamic monitoring system developed by Valley Group of the United States [63] has been popularized on more than 300 lines in 18 countries. The statistical results show that the transmission lines installed with a real-time DLR system can deliver 10%–30% more capacity in 90–120 days in a year, which brings extremely high economic benefits.

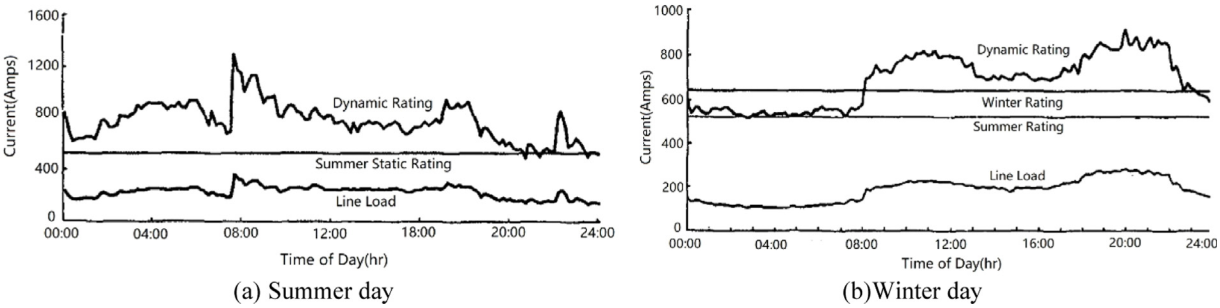


Fig. 6. Line load, dynamic rating, and static rating of the transmission line (New Zealand).

Transpower, a New Zealand power transmission company, applied DLR technology on two 220 kV transmission lines to improve the control ability of transmission lines [64]. The project used the CAT-1 DLR system to calculate the real-time maximum current capacity of transmission lines by directly measuring the tension of lines and the meteorological conditions. Fig. 6 shows the line load, dynamic rating, and static rating of one of the transmission lines in a typical summer and winter day. It can be seen from the figure that the dynamic rating of the transmission line is usually higher than the static rating of the line. The higher dynamic capacity of the line can be used to alleviate line capacity constraints and avoid unnecessary load reduction or downtime. Part of the time in the figure the dynamic rating is lower than the static rating may be caused by adverse weather conditions.

Some enterprises, universities, and power research institutions in China have also developed DLR systems for transmission lines and obtained some pilot applications. A DLR system, composed of conductor temperature monitoring module, meteorological data monitoring module, and computational analysis module, has been proposed by Zhejiang electric power company. With this system, the transmission capacity of lines can be improved while the safety and reliability of line operation can be guaranteed to avoid excessive load shedding in emergency situations [65]. The conductor temperature online monitoring devices of transmission lines and the DLR system developed by Xi'an Jiaotong University and Xi'an Jinyuan Electric Company adopt dual wireless communication to collect environmental information and conductor temperature, and calculates the hidden current carrying capacity of the transmission line by Morgan current carrying capacity formula [66]. The current capacity monitoring system of transmission line based on conductor tension and real-time meteorological developed by Shanghai Jiao Tong University can dynamically calculate transmission line rating through accurate and real-time monitoring of meteorological conditions, and has been put into operation on several 110 kV and 220 kV lines in China [67].

In view of the limited transmission capacity of 500 kV lines in East China power grid, the East China power grid corporation has developed a set of DLR system based on environmental information, line operation information, and data from SCADA system, and has been installed on several 500 kV lines for trial operation [46]. Fig. 7 shows the section line load, dynamic rating, and static rating of a 500 kV transmission line on August 29th, 2006. As can be seen from the figure, although the line load exceeded the static rating for some time, it did not exceed the dynamic rating of the transmission line. Therefore, the line was always running in a safe state. This line delivered about 675 MWh (shaded part in the figure) more electric energy on the same day by running the DLR system.

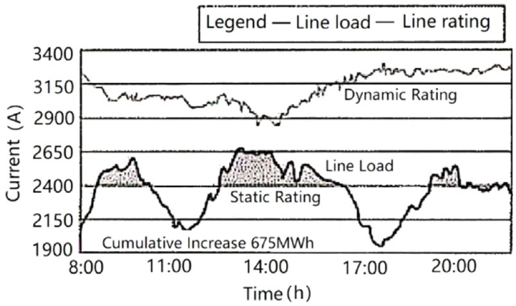


Fig. 7. Line load and rating of the transmission line (East China 500 kV/2006.08.29).

Chongming power company used both static and dynamic line rating technology at the same time in 220 kV Haizhong 4633/4634 lines to improve the transmission ability of the power transmission system [68]. The new static line rating was obtained by raising the upper limit of transmission line conductor temperature from 70 °C to 80 °C. Fig. 8 shows the power flow, static line rating, and dynamic line rating of Haizhong 4633/4634 lines on July 20th, 2009. It can be seen from the figure that although the power flow exceeded the original and static rating of the line for part of the time, it was always within the dynamic rating range. Therefore, the conductor temperature would not exceed the given limit. The total capacity increase time of Haizhong 4633/4634 lines was about 13.5 h, and the additional transmission capacity was 511 MWh, which effectively ensured the normal power supply during peak load of summer in Chongming island.

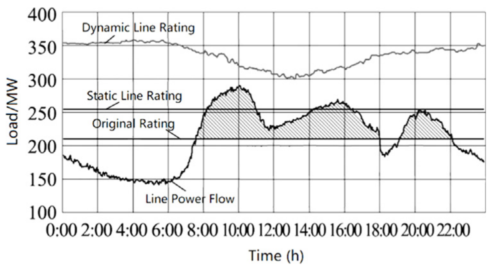


Fig. 8. Power flow and rating of the transmission line (Haizhong line 4633/4634 /2009.07.20).

DLR technology has been applied in some practical projects at home and abroad. However, the DLR technology is still in the stage of system operation effect evaluation and security verification of capacity increase at present in China. Therefore, the technologies such as accurate assessment and prediction of transmission line load capacity, risk assessment of capacity increase operation, optimization of dispatch assistant decision will become the key research directions of DLR technology in the future.

6. Conclusion

With the increasing demand for electricity and the increasing penetration rate of renewable energy, the technology of DLR has been widely concerned by scholars at home and abroad as an effective means to improve the transmission capacity of transmission lines and integrate renewable energy.

At present, the data acquisition technology and perception analysis technology of DLR technology have been widely studied at home and abroad. The developed DLR system has been applied in practical projects, but it has not been popularized in the power system. The main reason is that many problems that affect the reliability of DLR technology have not been resolved. The data quality of the transmission line data acquisition system is not high due to the unreliability of sensors, communication modes, and equipment power supplies. The existing transmission line analysis methods are still inadequate in terms of principles and applications. The architecture of the existing DLR system is open-loop, and the result of the system lacks effective verification means. There is a lack of research and risk assessment of transmission line DLR technology at the grid level.

Given the limitations of the existing DLR system, future research may include the following aspects:

(1) Improve the efficiency of effective data acquisition.

Optimize the installation methods and location of the sensors, improve the online rate of the monitoring devices, and realize the effective acquisition of key data. Reduce the types and number of online monitoring devices and reduce the requirements for communication systems. Rely on the existing micropower consumption and main network communication to improve the quality of data collected.

(2) Improve perception analysis methods

Improve the data processing and identification methods of transmission lines to enhance the processing ability of low-quality acquisition data; improve the deficiencies of existing analysis methods to enhance the accuracy and applicability of the DLR models; consider the real-time maximum current carrying capacity and the predicted maximum current carrying capacity of the transmission line comprehensively to provide a more comprehensive reference for the actual operation of the dispatching system.

(3) Design the closed-loop DLR system architecture

Introduce the modern control logic to build a closed-loop DLR system architecture. Introduce iterative correction into the model calculation, so that the analysis results will not completely depend on the wire parameters, reducing the influence of the time-varying characteristics of wire parameters on the analysis results.

(4) Evaluate the risk of DLR from the level of the whole power grid

Plan the dynamic capacity increase of transmission lines from the grid level, and take load forecasting, power generation plan and maintenance plan into consideration. Consider the security criterion constraints of the power grid in the process of dynamic capacity increase of transmission lines and evaluate the operational risk of the whole power grid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Rahman Mahbubur, Atchison Forest, Cecchi Valentina. Grid integration of renewable energy sources: utilization of line Thermal Behavior. In: Proceedings of 2019 SoutheastCon. Huntsville, AL, USA; 2019. p. 1–7.

[2] Xu Bolun, Ulbig Andreas, Andersson Göran. Impacts of dynamic line rating on power dispatch performance and grid integration of renewable energy sources. In: Proceedings of IEEE PES ISGT Europe 2013. Lyngby, Denmark; 2013. p. 1–5.

[3] Rácz Levente, Szabó Dávid, Göcsei Gábor, Németh Bálint. Grid management technology for the integration of renewable energy sources into the transmission system. In: Proceedings of 2018 7th international conference on renewable energy research and applications (ICRERA). Paris, France; 2018. p. 612–7.

[4] Madadi Sajad, Mohammadi-Ivatloo Behnam, Tohidi Sajjad. Dynamic line rating forecasting based on integrated factorized Ornstein–Uhlenbeck processes. IEEE Trans Power Deliv 2020;35(2):851–60.

[5] Douglass Dale A, Edris Abdel-Aty. Field studies of dynamic thermal rating methods for overhead lines. In: Proceedings of 1999 IEEE transmission and distribution conference (Cat. No. 99CH36333). New Orleans, LA, USA; 1999. p. 842–51.

[6] Douglass Dale A, Lawry Daniel C, Edris Abdel-Aty, Bascom Earle C. Dynamic thermal ratings realize circuit load limits. IEEE Comput Appl Power 2000;13(1):38–44.

[7] Douglass Dale A, Edris Abdel-Aty. Real-time monitoring and dynamic thermal rating of power transmission circuits. IEEE Trans Power Deliv 1996;11(3):1407–18.

[8] Wang Yong, Su Dawei, Xuesong, Zhang Ming, Feng Shuhai, Liu Jun. Dynamic transmission line capacity increase system with consideration of static power grid security. Electr Power Autom Equip 2017;37(2):199–204.

[9] Xu Wei, Bao Yanhong, Haifeng, Tang Wei, Liu Ludeng, ren Xiancheng, Xiang Xiaorong. Transmission line dynamic capacity-increase based on congestion analysis. Power Syst Prot Control 2016;44(6):15–22.

[10] Huang Xinbo, Sun Qindong, Han Xiaoyan. An on-line monitoring system of temperature of conductors and fittings based on GSM SMS and Zigbee. In: Proceedings of 2008 3rd IEEE conference on industrial electronics and applications. Singapore, Singapore; 2008. p. 1522–27.

[11] Gui Xun, Yao Lan, Liu Zhigang, Qian Qingquan. (2008). General power transmission line on-line monitoring software system based on wireless public network. In: Proceedings of 2008 7th world congress on intelligent control and automation. Chongqing, China; 2008. p. 2777–82.

[12] Xie Kai, Zhao Yanshuang, Zhang Hongying, Lu Zhongbin, Chai Quan, Zhang Jianzhong. Practice of optical fiber sensing technologies in power transmission lines and towers. In: Proceedings of 2018 international conference on power system technology (POWERCON). Guangzhou, China; 2018. p. 3912–8.

[13] Yoo Wook Jae, Cho Dong Hyun, Jang Kyoung Won, Shin Sang Hun, Seo Jeong Ki, Chung Soon-Cheol, Tack Gye-Rae, Lee Bongsoo, Park Byung Gi, Moon Joo Hyun, Kim Sin. (2008). Infrared fiber-optic sensor for non-contact temperature measurements. In: Proceedings of 2008 3rd International Conference on Sensing Technology, Tainan, Taiwan, China, (2008): 500-503.

[14] Foss Stephen D, Lin Sheng H, Carberry Robert. Significance of the conductor radial temperature gradient within a dynamic line rating methodology. IEEE Power Eng Rev 1987;PER-74(1987):60.

[15] Gore Rahul N, Valsan Simi P. Wireless communication technologies for smart grid (WAMS) deployment. In: Proceedings of 2018 IEEE international conference on industrial technology (ICIT). Lyon, France; 2018. p. 1326–31.

[16] Du Lin, Wang Caisheng, Li Xianzhi, Yang Lijun, Mi Yan, Sun Caixin. A novel power supply of online monitoring systems for power transmission lines. IEEE Trans Ind Electron 2010;57(8):2889–95.

[17] Chu Qiang, Zhang Jiancheng, Li Gang. Power supply of transmission line online monitoring system based on super-capacit. Electr Power Autom Equip 2013;33(3):152–7.

[18] Shi Mingqi, Wang Xiaolan. Design of hybrid energy harvesting self-powered power supply for transmission line sensor. In: Proceedings of IOP Conference series: earth and environmental science. Xi'an, China; 2020.

[19] Zhao Long, Huang Xinbo. Integrated condition monitoring system of transmission lines based on fiber bragg grating sensor. In: Proceedings of 2016 international conference on condition monitoring and diagnosis (CMD). Xi'an, China; 2016. p. 667–70.

[20] Divya Shree M, Sangeetha A, Krishnan Prabu. Analysis and optimization of uniform FBG structure for sensing and communication applications. Photon Netw Commun 2020;39(3):223–31.

[21] Gal Stelian Alexandru, Oltean Marius Nicolae, Brabete Lucian, Rodean Ioan, Opincaru Mircea. On-line monitoring of OHL conductor temperature; Live-line installation. In: Proceedings of 2011 IEEE PES 12th international conference on transmission and distribution construction, operation and live-line maintenance (ESMO). Providence, RI, USA; 2011. p. 1–6.

[22] Talpur Saifal, Lie TT, Zamora R. Application of dynamic thermal rating: Overhead line critical spans identification under weather dependent optimized sensor placement. Electr Power Syst Res 2020;180.

[23] The Jiashen, Cotton Ian. Critical span identification model for dynamic thermal rating system placement. IET Gener Transm Distrib 2015;9(16):2644–52.

[24] Tronchoni Alex B, Bretas Arturo S, Gazzana Daniel S. Two-dimensional transmission line modeling method: An algorithm considering non-homogeneous media and ionization. Electr Power Syst Res 2019;173(2019):220–9.

[25] Zhang Jiarui, Liu Xiaosheng, Chen Pengfei, Pu Honghong, Xu Dianguo. A networking method for power line communication based on stereo mesh network. In: Proceedings of 2019 22nd international conference on electrical machines and systems (ICEMS). Harbin, China; 2019. p. 1–5.

[26] Meka Srikar, Fonseca Benedito. Improving route selections in zigbee wireless sensor networks. Sensors (Switzerland) 2020;20(1).

[27] Reddy Yeduri Sreenivasa, Panda Meenakshi, Dubey Ankit, Kumar Abhinav, Panigrahi Trilochan, Rabie Khaled M. Optimisation of indoor hybrid PLC/VLC/RF communication systems. IET Commun 2020;14(1):117–26.

[28] Rácz Levente. Dynamic line rating - Investigation of dynamic line rating based on black box modeling [M.Sc. thesis], Budapest University of Technology and Economics; 2019.

[29] Ringelband Tilman, Lange Matthias, Dietrich Martin, Haubrich Hans-Jurgen. Potential of improved wind integration by dynamic thermal rating of overhead lines. In: Proceedings of 2009 IEEE bucharest powertech. Bucharest, Romania; 2009. p. 1–5.

[30] Berende MJC, Slootweg JG, Clemens GJMB. Incorporating weather statistics in determining overhead line ampacity. In: Proceedings of 2005 international conference on future power systems. Amsterdam, Netherlands; 2005. p. 8.

[31] Calculating the current-temperature of bare overhead conductors. IEEE Standard 2006;738.

[32] Thermal behaviour of overhead conductors. CIGRE Standard 2002;207.

[33] Overhead electrical conductors—calculation methods for stranded bare conductors. 1995, IEC TR 61597.

[34] Szabó Dávid. Development of dynamic line rating system [M.S. thesis], Budapest, Hungary: Budapest University of Technology and Economics; 2019.

[35] Morrow David John, Fu Jiao, Abdelkader Sobhy Mohamed. Experimentally validated partial least squares model for dynamic line rating. IET Renew Power Gener 2014;8(3):260–8.
[36] Fu Jiao, Abdelkader Sobhy, Morrow D John, Fox Brendan. Partial least squares modelling for dynamic overhead line ratings. In: Proceedings of 2011 IEEE Trondheim PowerTech. Trondheim, Norway; 2011. p. 1–6.
[37] Fu Jiao, Abbott SR, Fox Brendan, John Morrow D, Abdelkader Sobhy. Wind cooling effect on dynamic overhead line ratings. In: Proceedings of 45th international universities power engineering conference UPEC2010. Cardiff, Wales, UK; 2010. p. 1–6.
[38] Fu Jiao, John Morrow D, Abdelkader Sobhy M. Modelling and prediction techniques for dynamic overhead line rating. In: Proceedings of 2012 IEEE power and energy society general meeting. San Diego, CA, USA; 2012. p. 1–7.
[39] Rácz Levente, Németh Bálint. Investigation of dynamic electricity line rating based on neural networks. Energetika 2018;64(2):74–83.
[40] Rácz Levente, Szabó Dávid, Göcsei Gábor, Németh Bálint. Application of monte carlo methods in probability-based dynamic line rating models. In: Proceedings of 10th advanced doctoral conference on computing, electrical and industrial systems DoCEIS 2019. Caparica, Portugal; 2019. p. 115–24.
[41] Zhang Jun, Pu Jian, McCalley JD, Stern Hal, Gallus WA. A Bayesian approach for short-term transmission line thermal overload risk assessment. IEEE Trans Power Deliv 2002;17(3):770–8.
[42] Ringelband Tilman, Schäfer Philipp, Moser Albert. Probabilistic ampacity forecasting for overhead lines using weather forecast ensembles. Electr Eng Arch Elektrotech 2013;95(2):99–107.
[43] Aznarte José L, Siebert Nils. Dynamic line rating using numerical weather predictions and machine learning: A case study. IEEE Trans Power Deliv 2017;32(1):335–43.
[44] Fernandez Elvira, Albizu Igor, Buigues Garikoitz, Valverde Victor, Etxegarai Agurtzane, Olazarri Jon G. Dynamic line rating forecasting based on numerical weather prediction. In: Proceedings of 2015 IEEE Eindhoven PowerTech, Eindhoven, Netherlands; 2015. p. 1–6.
[45] Molinar Gabriela, Fan Lintao Toni, Stork Wilhelm. Ampacity forecasting: an approach using Quantile Regression Forests. In: Proceedings of 2019 IEEE power & energy society innovative smart grid technologies conference (ISGT). Washington, DC, USA; 2019. p. 1–5.
[46] Yang Yi, Harley Ronald G, Divan Deepak, Habetler Thomas G. Thermal modeling and real time overload capacity prediction of overhead power lines. In: Proceedings of 2009 IEEE international symposium on diagnostics for electric machines, power electronics and drives. Cargese, France; 2009. p. 1–7.
[47] Madadi Sajad, Nazari-Heris Morteza, Mohammadi-Ivatloo Behnam. Application of fuzzy methods in power system problems. In: Handbook of neural computation. Amsterdam, the Netherlands: Elsevier Inc.; 2017, p. 551–70.
[48] Huang Xinbo. Online monitoring and fault diagnosis of transmission lines. China: China Electric Power Press; 2014, p. 169–201.
[49] Li Peng, Huang Xinbo, Zhao Long, Zhu Yongcan. Research and design of transmission line condition monitoring agent. Proc Chinese Soc Electr Eng 2013;33(16):153–61.
[50] Zhou Zandong, Gou Xiaokan, Zeng Shengqiang. Modular calculate research on dynamic capacity-increase of transmission lines. Energy Res Manag 2017;55–7.
[51] Dupin Romain, Kariniotakis George, Michiorri Andrea. Overhead lines dynamic line rating based on probabilistic day-ahead forecasting and risk assessment. Int J Electr Power Energy Syst 2019;110:565–78.
[52] Ying Zhanfeng, Xu Jie, Zhang Xudong, Du Zhijia, Zhao Qian. Risk assessment of dynamic overhead lines rating based on thermal circuit model considering pulsating characteristic of parameters. Autom Electr Power Syst 2015;39(23):89–95.
[53] Kim Dong-Min, Park Yeong-Hyeon, Bae In-Su, Kim Jin-0. Decision of transmission line rating based on assessment of Thermal Overload Risk. In: Proceedings of 2006 eleventh international middle east power systems conference, El-Minia, Egypt; 2006. p. 366–70.
[54] Wang Kongsen, Sheng Gehao, Jiang Xiuchen. Risk assessment of transmission dynamic line rating based on Monte Carlo. In: Proceedings of 2011 IEEE power engineering and automation conference. Wuhan, China; 2011. p. 398–402.
[55] Dupin Romain, Michiorri Andrea, Kariniotakis George. Optimal dynamic line rating forecasts selection based on ampacity probabilistic forecasting and network operators' risk aversion. IEEE Trans Power Syst 2019;34(4):2836–45.
[56] Wang Cheng, Gao Rui, Qiu Feng, Wang Jianhui, Xin Linwei. Risk-based distributionally robust optimal power flow with dynamic line rating. IEEE Trans Power Syst 2018;33(6):6074–86.
[57] Tschampion Michael, Bucher Matthias A, Ulbig Andreas, Andersson Göran. N-1 security assessment incorporating the flexibility offered by dynamic line rating. In: Proceedings of 2016 power systems computation conference (PSCC). Genoa, Italy; 2016. p. 1–7.
[58] Weedy BM. Dynamic current rating of overhead lines. Electr Power Syst Res 1989;16(1):11–5.
[59] Moore T. Dynamic ratings boost transmission margins. EPRI J 2000;25(1):18–25.
[60] Douglass Dale, Chisholm William, Davidson Glenn, Grant Ian, Lindsey Keith. Real-time overhead transmission-line monitoring for dynamic rating. IEEE Trans Power Deliv 2016;31(3):921–7.
[61] Dai Yuan, Cheng Yangchun, Zhong Wanli. Dynamic line rating for high-voltage overhead transmission lines. Beijing, China: China Electric Power Press; 2013.
[62] Yip Tony, An Chang, Lloyd Graeme, Aten Martin, Ferri Bob. Dynamic line rating protection for wind farm connections. In: Proceedings of 2009 CIGRE/IEEE PES joint symposium integration of wide-scale renewable resources into the power delivery system. Calgary, AB, Canada; 2009. p. 1–5.
[63] The Valley Group. CAT-1 transmission line monitoring system. 2006.
[64] Raniga JK, Rayudu RK. Dynamic rating of transmission lines-a New Zealand experience. In: Proceedings of 2000 IEEE power engineering society winter meeting. Conference proceedings (Cat. No.00CH37077), Singapore, Singapore; 2000. p. 2403–9.
[65] Sheng Gehao, Liu Yadong. Principles and key technologies of intelligent transmission lines. Beijing, China: Science Press; 2017.
[66] Wu Wenxuan, Chen Jinxiang, Lin Liqin. Test and application study of allowable dynamic carrying capacity on transmission lines. In: Proceedings of 2011 international conference on electric information and control engineering. Wuhan, China; 2011. p. 4560–4.

[67] Ren Lijia, Sheng Gehao, Li Lixue, Zeng Yi, Jiang Xiuchen. Research of dynamic line rating system. Autom Electr Power Syst 2006;30(17):45–9.

[68] Chen Gang, Chen Jianfeng, Wu Rong, Fan Bing, Jin Heng. Application of transmission lines capacity boosting technology in chongming grid. East China Electr Power 2009;37(8):1364–6.